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Chapters 4 to 5

**DEVELOPING ARTIFICIAL LIFE SIMULATIONS
OF VEGETATION TO SUPPORT THE VIRTUAL
RECONSTRUCTION OF ANCIENT LANDSCAPES**

By
Eugene Ch'ng
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The University of Birmingham
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School of Engineering
Department of Electronic, Electrical & Computer Engineering
The University of Birmingham
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Chapter 4

Models of Vegetation Artificial Life and Its Ecology

4.1. Introduction

The diversity of the planet's vegetation and environmental conditions support a complex web of interaction that manifest emergence in both structure and pattern and dictates availability of resources and space on terrains. Modelling plant life in order to study their behaviours for solving the evolution of landscapes is difficult, requiring not only the knowledge of their structures but also the natural habitat on which they thrive. These complexities in natural life make artificial life concepts an appropriate technique for modelling them. As John Holland taught [157], the program for studying emergence depends on reductionism, and that "... complicated systems are described in terms of interactions of simpler systems ...". In the context of the research reported in this chapter, the goal is to model these simpler systems – the plants themselves – from the more complicated emergent systems resulting from the interaction between those plants, their local habitat and the environment. This will be achieved through the "extract[ion of] the regularities from incidental and irrelevant details" [157].

Previous research has largely been focused on the simulation of vegetation of woodland types using GIS, known to possess various limitations (see section 1.2.4 and 2.5). Furthermore, structural models of alife vegetation and its growth have been demonstrated in related research (See section 2.4.3). These, together with agent-based models of vegetation (See section 2.4.4) have either been too resource intensive for large landscapes, or have been partial and insufficient for modelling vegetation lifecycle and their interactions in the niches of their abiotic and biotic environments. These simulations are mainly static in nature (not real-time and non-interactive), with predictions in a certain region at a certain time based on vegetation preferences of climate, temperatures and soil conditions or even none at all. The objective of the present research is not to develop the simulation of vegetation in the traditional way, but to model the vegetation and represent collective

dynamics using a novel approach by taking into account the lifecycle of each vegetation entities based on the concept of decentralisation [180] and the emergence in global patterns from their local interactions. In such a system, each individual alife entity has equal ground in the competition for resources without intervention by a central command. These characteristics are analogous with that observed in physical vegetation and other natural systems. Simulations of this kind are “microanalytic” or “agent-based”, in that they simulate each component of the evolving system and its local interactions so that more global dynamics emerge. This “microanalytic” strategy is the hallmark of artificial life models [153]. Emergence is the process that delivers *something* more than the sum of their computational parts. On this, Whitelaw [205] stated that “*something* may be in the form of a spatial pattern or form”, which may eventually solve problems in the domain of the research presented here. Furthermore, by integrating alife within a Virtual Environment, an interactive layer is introduced that will demonstrate the dynamics of the model, enabling us to investigate, as well as to explore, the alife terrain.

The intricacy of a plant can be seen in its life cycle [314, 315]. A seed contains genetic materials with coded characteristics that define specific instructions for building a full grown tree. That tree will eventually produce new generations of seeds via its reproductive lifecycle. Germination, coupled with the inevitable struggle against other plants, organisms and the environment are vital processes, the success of which dictates the ability of the species to survive and continue over many centuries, if not millenniums. Each of these stages, multiplied by the diversity of vegetation in their growth and reproduction, makes modelling every aspect of it difficult, even with the powerful computing facilities we possess today. The structure of a plant, from its rooting system to the branches and leaves, and the way water and minerals are conducted from roots to leaves, present even more layers of complexity. Furthermore, there are competitions amongst and between plants, influenced by the preferences and tolerance of different species towards the availability of natural resources. The environment provides another obstacle, with its complex biochemical influences on soil quality, not to mention atmosphere, and climatic variations. However, a practical approach, using alife concepts, is to model life sufficiently to achieve or approximate a set of objectives appropriate to the end application. This is the process of abstraction for the purpose of synthesising life. “alife does not propose to encourage an obsessive strive towards perfection in simulating living organisms, but rather supports an abstract distillation of ‘aliveness’, life itself, ‘re-embodied in voltage and silicon’” [205]. For example, in order to add realism to a virtual aquarium application, as may be used in tourism entertainment systems, it may

be sufficient simply to programme the fish to react to threats from predators by setting rules for “fleeing”. In contrast, attempting to add evolutionary algorithms into the alife of the aquarium would possibly be considered as “overkill”, given the aim of the application. Similarly, reproduction may be a superfluous component of the modelling of the reef fish, unless another objective of the virtual aquarium application demands educational integration. In imitating flocks of birds [194], physics and gravity are not taken into account in the design. Instead, three sets of simple rules (separation, alignment and cohesion) are observed and distilled from the patterns into program codes for the simulation, resulting in a flocking behaviour. Life is “a property of the organisation of matter” and “living organisms are nothing more than complex biochemical machines” as taught by Langton [163, 204]. Such definitions gave a notion of life that is wholly materialistic, “involving no soul, vital force, or essence” [205]. These concepts are practically important to the way in which vegetation can be modelled.

By adopting alife approaches to solve problems in the present research domain and by studying the preferences and behaviour of vegetation (abstracting prominent characteristics into algorithmic rules), its behaviour can be simulated with the aim of “clothing” a barren virtual landscape with a living forest that thrives within the confines of voltage and silicon. The generalisation of properties specific to vegetation will support the inclusion of plants other than woodland types (as are the norm in traditional models for determining vegetation growth on landscape). This will deliver a much larger picture of the struggle for existence, where survival of the fittest thrive in a competitive environment [186]. In this way, the benefit of the bottom-up approach in alife endeavours may become manifest as self-organisation of different species striving for resources emerge as dynamic patterns in what we recognised as natural landscapes. “Only when we sketch these biomes – natural communities of wide extent, characterised by distinctive, climatically controlled group of plants and animals – in terms of trees and shrubs and grasses can we fill in other features, such as deer, antelope, rabbits, or wolves ...” [20], possibly humans as well.

The chapter begins with a description of an artificial life framework created specifically for studying ancient vegetation distribution patterns. The framework, a games engine architecture and the “host” VE for visualisation is presented with all technical aspects of its design and implementations. The major research in this chapter mainly describes the abiotic and biotic aspects related to alife-based vegetation modelling, detailing the generalised rules and properties distilled

from knowledge and observation of vegetation and its ecology. The chapter concludes with a summary of the text.

4.1.1. An Artificial Life Framework

In order to develop and experiment with the model, a test bed is mandatory. Two requirements are necessary for this exercise – simulation and visualisation. A survey of games engines at the initial stages of this research did not yield an appropriate system suited to this need even though the capability of some engines may be used later for interactive visualisation purposes described in Chapter 3. Thus, the creation of a framework is needed. The *SeederEngine* [316, 317], an artificial life framework, a tool for conducting vegetation ecological modelling research is the outcome of the continual development and improvement in the length of this study. Developing a dedicated engine allows the exclusion of unnecessary features in standard engines that may slow down the system and provides a greater control of alife algorithms in the research.

4.1.2. Engine Architecture

The engine architecture is composed of various modules, each having its functional purpose benefiting the totality of the system. The engine is the major part of a pipeline of tools developed for conducting the Virtual Heritage research presented here. Microsoft's DirectX 9.0c API is used for developing the engine together with the Object-Oriented of the C# programming language to build the simulation environment, artificial life entities, and optimisation algorithms.

The diagram in Figure 42 shows the architecture as part of the Virtual Heritage pipeline instrumental in the accomplishment of this research. The diagram shows that content is generated based on knowledge obtained from studies in archaeology, geology, and botany. The contents, in both 3D models and textures, and parameters of vegetation and its ecology are passed into the simulation framework for modelling vegetation distribution patterns. The outcome of the simulation is exported and recreated in a Serious Gaming environment such as Ubisoft's FarCry™. Finally the real-time interactive Virtual Environment can be disseminated to interested parties.



A Pipeline of Tools for Virtual Heritage Creation

Figure 42. The position of *SeederEngine* within the pipeline of tools for Virtual Heritage creation

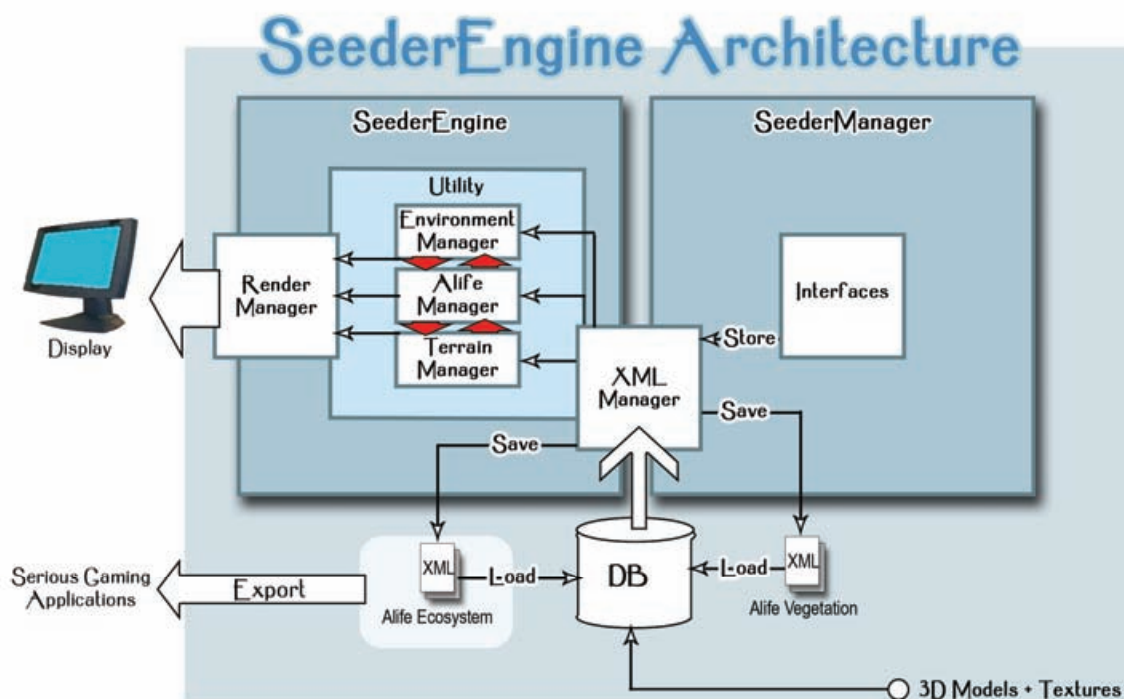


Figure 43. A detailed view of the *SeederEngine* architecture

Figure 43 is a detailed view of the modules within the architecture. Two software systems are incorporated within the architecture, both sharing modules and resources. The *SeederManager* is

an interface for managing ecosystems, vegetation species, and vegetation communities within the ecosystem. It consists of two interfaces. The ecosystem interface contains a map editor for positioning vegetation communities within the terrain and settings for changing the parameters of the ecosystem. Terrains can be changed by loading new ones. Ground information (Ground Info) related to soil acidity, soil depth, and generic soil conditions can be set within the interface. The plant manager interface provides a way to adjust a plant species' preferences, lifecycle parameters, and 3D representations of each phase within the lifecycle (seed-seedling-young-mature-old). The *MapPlant* module stores plant information related to the terrain. The data managed in the *SeederManager* uses the *XML Manager* as a database system for loading and saving ecosystems and plants.

SeederEngine hosts the real-time VE. It shares the *XML Manager* module with *SeederManager* and uses five other modules for powering the engine: *Environment Manager*, *Terrain Manager*, *alife Manager*, *Render Manager*, and *Utility*. The Environment, alife, and Terrain Manager continually accesses each others information through the engine. At runtime, users have access to parameter settings in the *Environment Manager*, *Render Manager*, and *Terrain Manager* for adjusting global conditions such as temperature increment, water-level and hydrology, global moisture, sunlight, elevation, pH level, fog, and three rendering modes of solid, wireframe, and points.

The *Environment Manager* contains a mechanism for automating the variations that occur in environmental parameters, such as the fluctuations of temperature, moisture, and sunlight. It also contains ground information (Ground Info) to determine, on a local scale, which parts of the landscape has higher acidity, shallower soil depth, and difficult soil conditions. *Terrain Manager* manages the 3D terrain and water level.

The strength of the system lies in the *alife Manager* which handles all the modelling aspect related to vegetation Artificial Life. The module is designed with extensibility in mind and is capable of including life forms other than vegetation. For example, the *Organism* superclass in Figure 44 can be extended to include classes such as Mammal, Insect, and etc.

The *Utility* module contains useful generic functions for tying all the modules together. As an example, 3D models imported from third-party software may have a different unit settings, the unit

conversion function converts them into a universal unit of measure. The module also contains functions and sub-modules for loading 3D models, and functions for calculating angles and distances in 3D space for plant orientation and seed distribution during plant propagation. Other important features within the module are Texture Pool, Temperature Variation Dataset, Plant Migration Dataset, and Segmentation. The Texture Pool optimises resource usage by loading into memory textures that have not been loaded, thus preventing memory bottlenecks. The Temperature Variation Dataset handles temperature increment/decrement presets for large timescales. The Migration Dataset handles all migrating plants according to preset time, species, number of plants, and age groups. The Segmentation module segments groups of plants on the terrain into competing units to prevent distant plant from being taken into consideration, this can considerably save CPU time during simulations.

The UML diagram in Figure 44 describes, from a high-level view, the interaction of these modules.

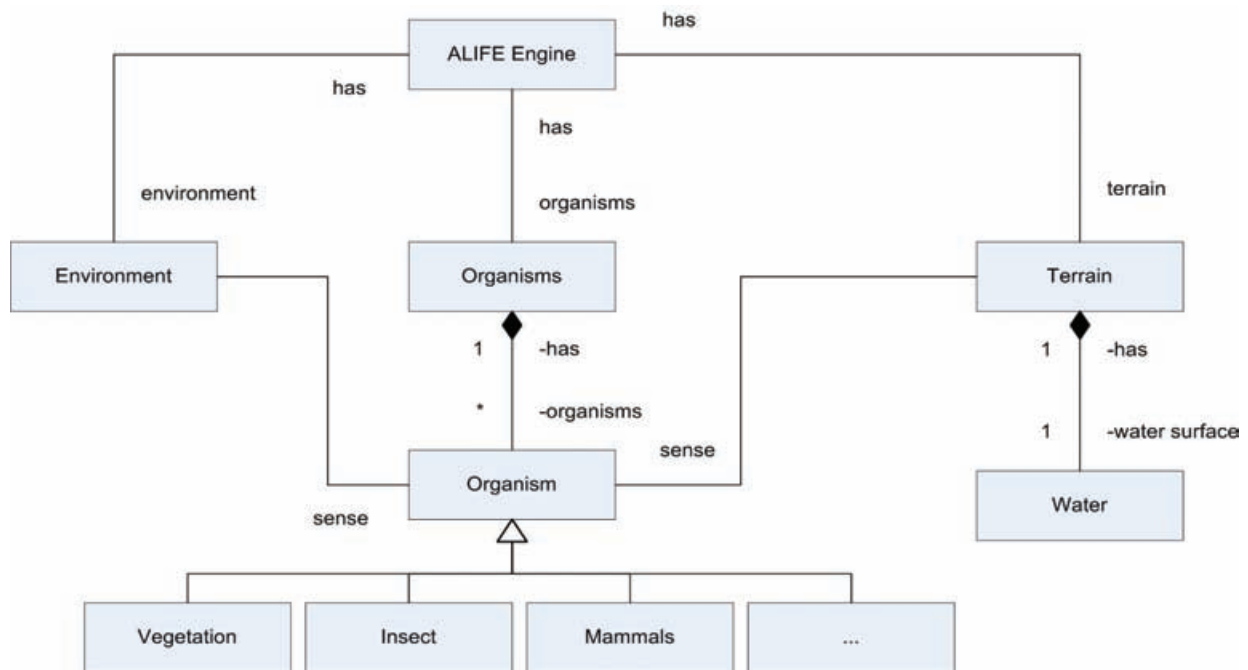


Figure 44. A UML diagram showing the interaction of modules

4.1.3. Engine Capabilities

During the design stages, considerations were that the engine should at least support the basic functionality of a real-time Virtual Environment with living Artificial Life entities. A scheme was carefully planned so that important functionality was weighted and features considered unnecessary are excluded from the system. However, this does not mean that the system cannot be enhanced in future research. In the plan, it was predicted that most computing resources should be channelled for alive computations since it will host thousands of plants. Therefore interactivity and rendering quality was kept to a minimum as techniques in computer graphics could later fill up this lack, or the system could be improved in future work. These basic features have been implemented and are listed below:

- Real-time rendering
- Supports standard 3D geometry import for objects and terrains
- Basic navigation
- Interactivity with ecosystem
- Customisable plant species and representation
- Customisable environments and terrains
- Map editor
- Load/save features
- Supports generic Artificial Life vegetation and behaviours
- Supports a five level interpolated vegetation representation
- Extensible for other Artificial Life forms (Object-Orientation)
- Plant migration settings
- Large-timescale temperature variations
- Environmental variations (sunlight, moisture, temperature, CO₂, etc)
- Bi-directional plant-environment affecters
- Local ground condition
- Large index optimisation/ Segmentation algorithm

4.1.4. Artificial Life Software Framework

The alife software framework was built to allow replacements of behaviours of organisms and laws within the Virtual Environment. Many behavioural studies of vegetation are hypotheses and therefore certain assumptions have to be made for modelling them. This is via observations and statistical studies in nature. In the alife framework, these behaviours can be replaced with newer ones once the facts have been established. Designing the framework in such a way will also assist studies in Artificial Life in establishing facts for knowing life-as-it-could-be via the manipulation of the parameters of life. Figure 45 illustrates the concept. Inputs of ecological laws of the environment are sensed by the plant entity, which receives the behaviour assumptions and is measured by the *adaptability function*. The results of the measure are then channelled through the fitness function to determine the health of the plant. The input laws and behaviours are equations and algorithms. Each law and behaviour can be replaced with newer ones from established facts. Changing the laws and behaviours may result in different outcomes in the collective vegetation dynamics. An open extension can be incorporated in the Environment to allow input streams of live information in future work.

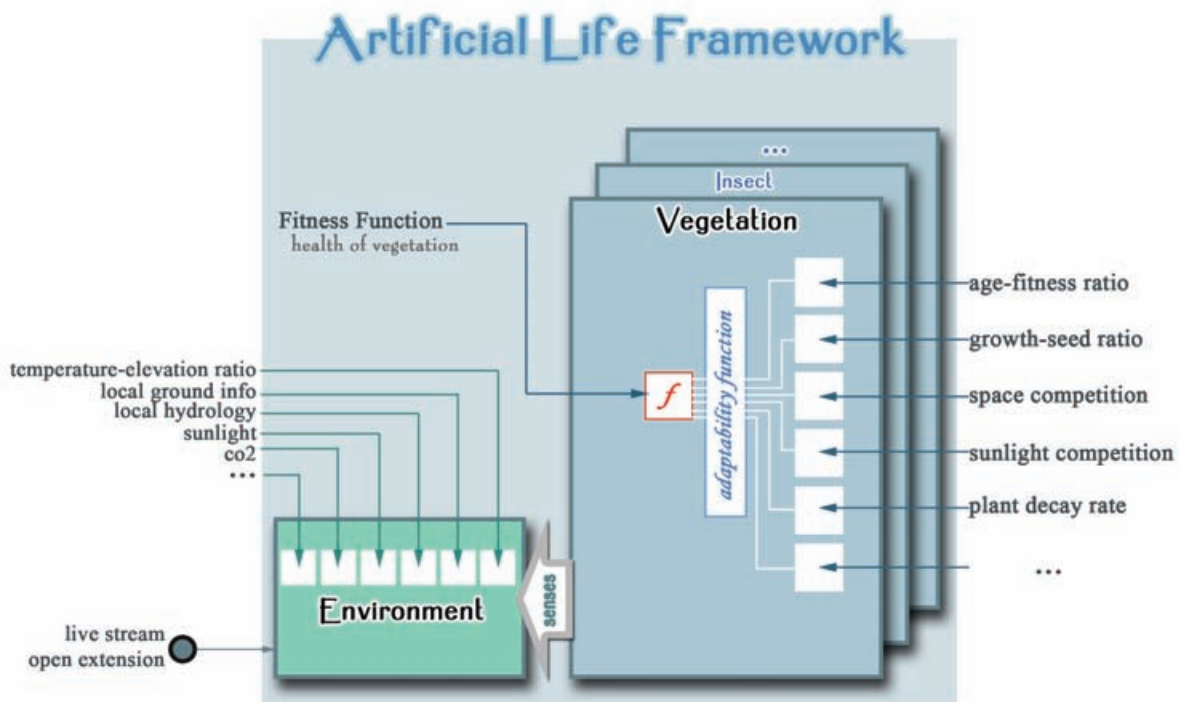


Figure 45. The Artificial Life framework for vegetation and ecosystem. The external inputs are 'plug-in' equations and algorithms

4.1.5. SeederManager User Interfaces

There are two interfaces for *SeederManager*. The main interface shown in Figure 46 provides various tabs for settings such as the environment, map editor, plant migration, temperature variations, ground info, and ecosystem build. The second interface manages plant behaviours.

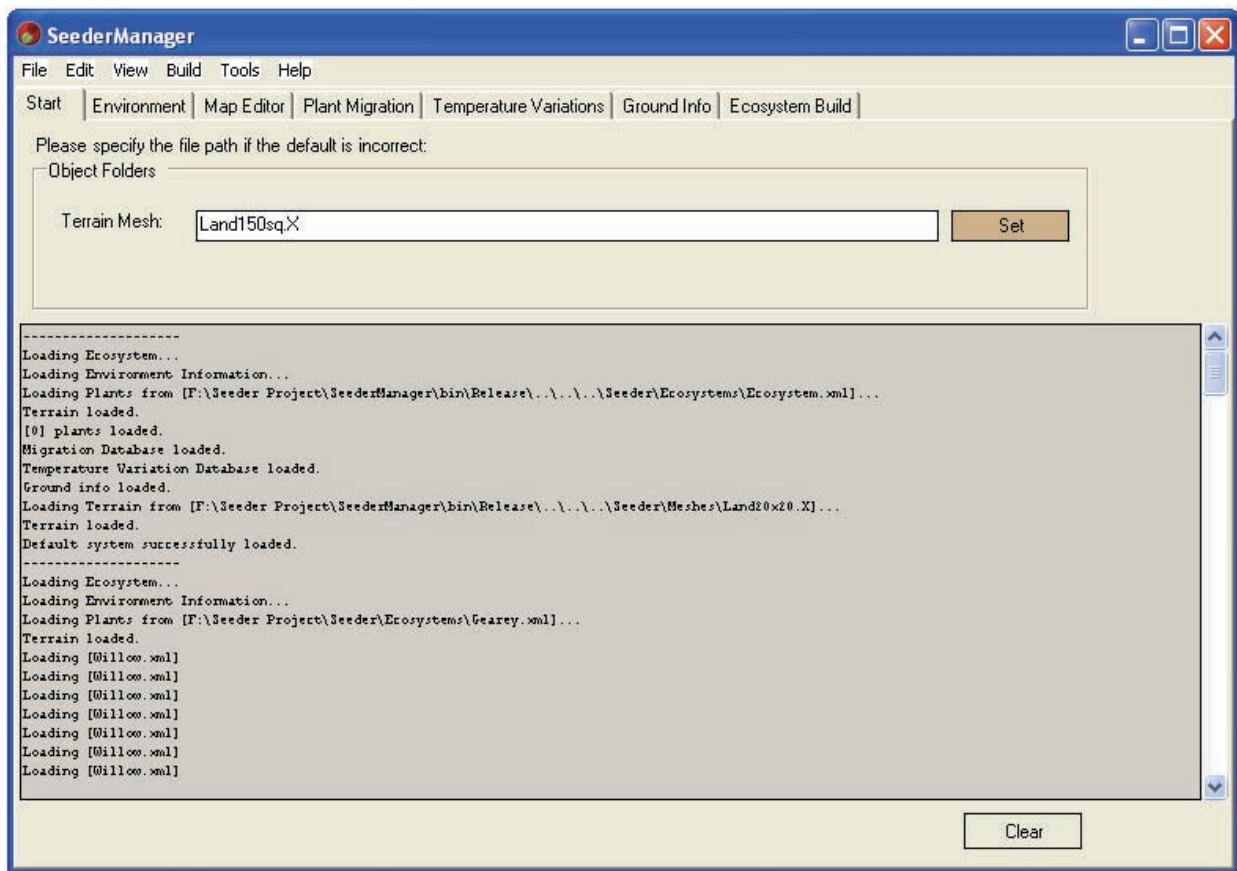
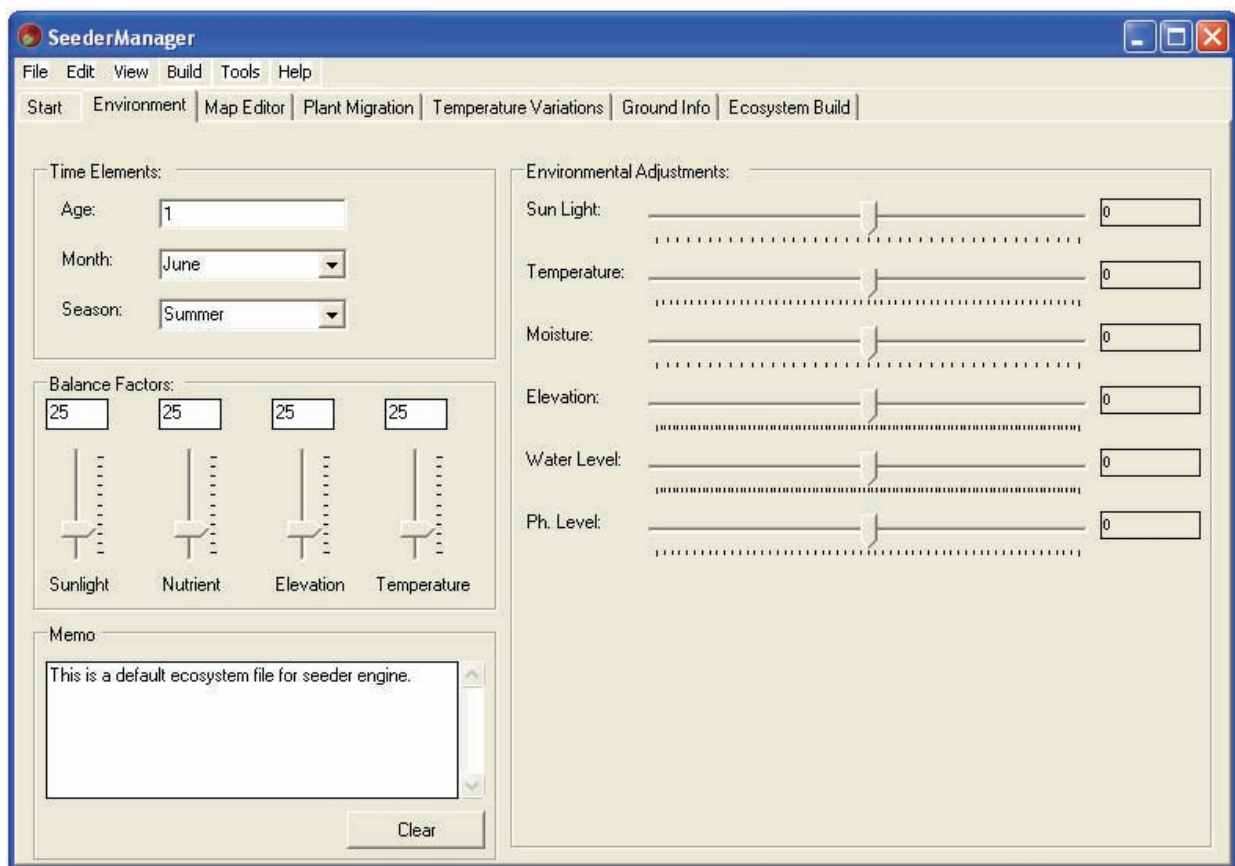


Figure 46. *SeederManager* – Main interface

Figure 47. *SeederManager* – Environment settings tab

The environment tab (Figure 47) allows the control of settings related to initial time elements, balance factors, and environmental adjustments. Balance factors are weights for determining which factors (sunlight, nutrient, elevation, temperature) are more important in affecting the fitness of vegetation. The interface shows a preset of equal distribution of weights for all factors. Environmental adjustments allow the increment/decrement of global conditions. For example, in order to start an ecosystem at a slightly lower temperature, the temperature track bar could be set to -2°C. The interface has the default setting of zero for all environmental factors.

Figure 48 shows the map editor, the plant migration tab, and the temperature variation tab. Different coloured geometry in the map editor shows different species acquired from the plant list on the left. Insertion of plants onto the map can be single or a spray of random clusters with settings of the number of plants and distances from the insertion point. The age and initial life of a plant can also be set. The plant migration tab shows three migration sets at year 200, year 400 and year 500 of the Hazel, Elm, and Oak species with the number of migrating plants and their age

respectively. The temperature variation tab shows an increment of 1.7°C for every 100 years for four consecutive periods.

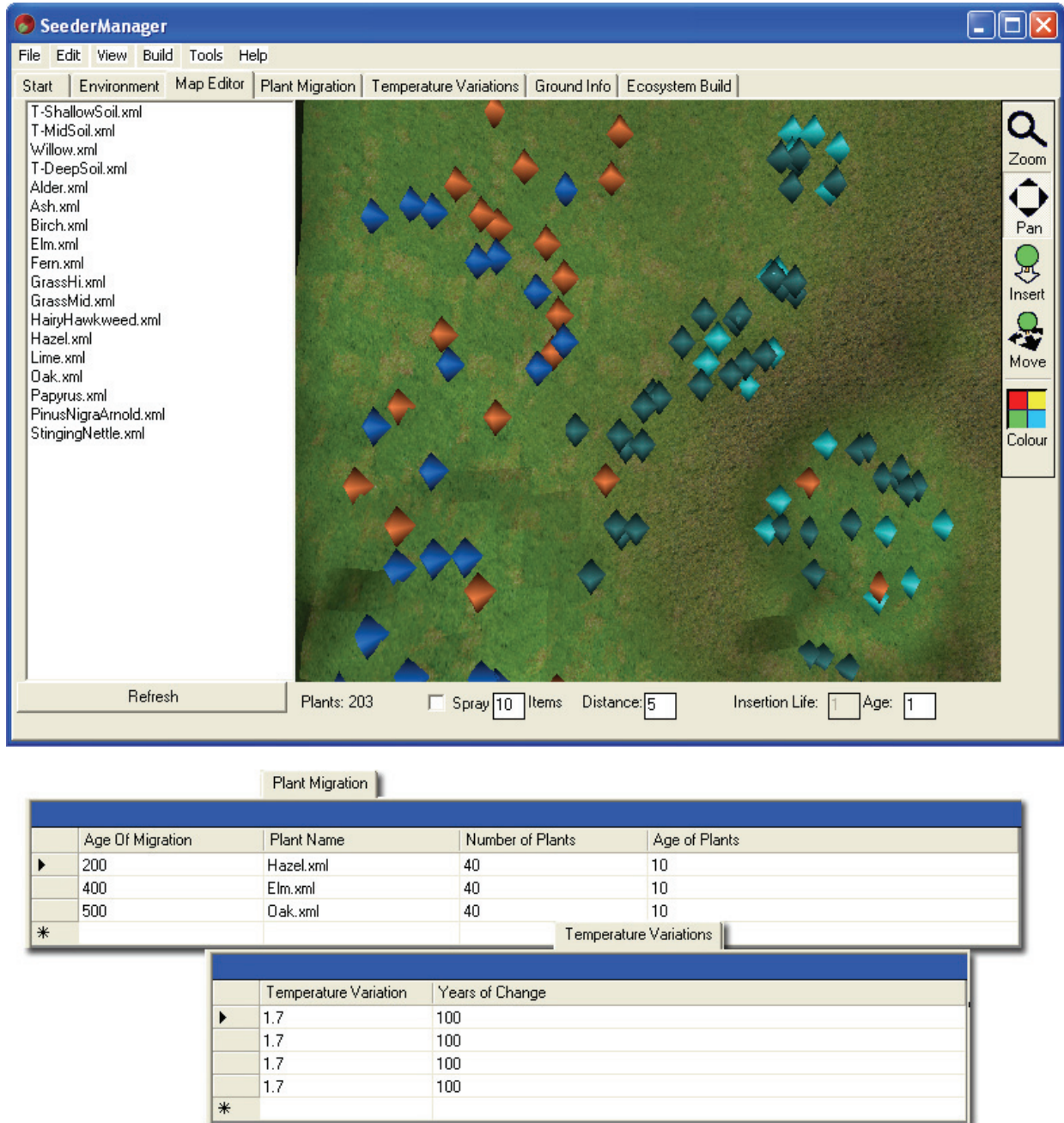


Figure 48. *SeederManager* – Map editor

When the settings are finalised, the ecosystem is saved as an XML file. Figure 49 shows the main interface of the Plant Manager loaded with the Hazel species. Figure 50 is the plant tolerance

tab (adaptability settings). The settings determine the adaptability, competitiveness, and fitness of the alife-based vegetation via the alife framework.

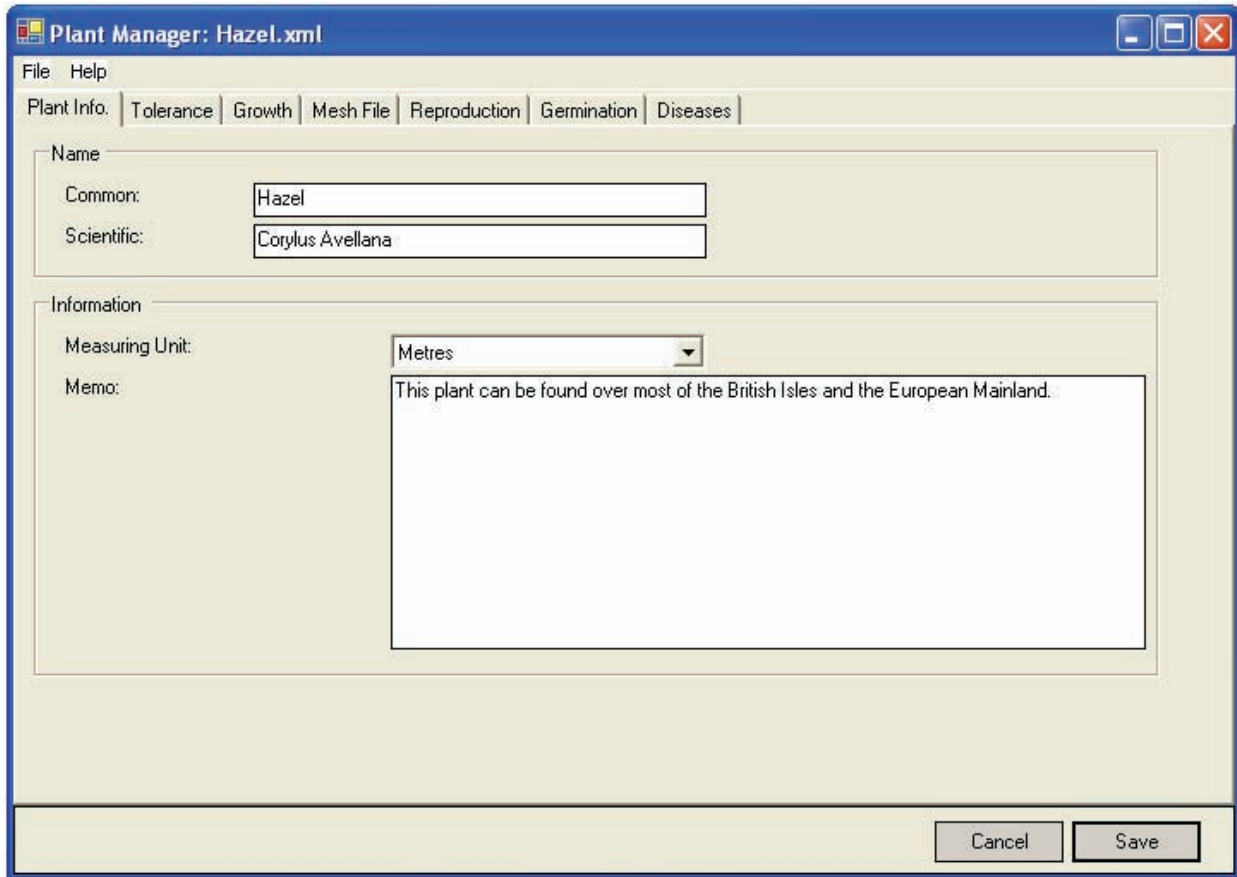


Figure 49. *Plant Manager* – Main interface

Figure 51 are screenshots of tabs within the Plant Manager. The 'Growth' tab allows the growth characteristics of the plant to be specified and have direct impact on its competitiveness in the landscape. The 'Reproduction' tab specifies the age of sexual maturity, time of reproduction, and reproduction characteristics. The settings in the 'Germination' tab are related to the expiration and adaptability of the seeds when it has been dispersed. The 'Mesh File' tab specifies a five-level 3D representation of the vegetation in the Virtual Environment.

Figure 52 shows a tab for specifying diseases common to vegetation. At this stage, diseases are not taken into consideration in the model as no information regarding its relationship with ancient plants can be obtained. Nevertheless, the tab is left open for future implementations.

Tolerance

Moisture Preferred: [0.47] Upper: [0.56] Lower: [0.33]		Sun Light Preferred: [0.4] Upper: [0.6] Lower: [0.25]	
Nutrients Preferred: [0.5] Upper: [0.6] Lower: [0.4]		Temperature Preferred: [20°C] Upper: [30°C] Lower: [5°C]	
Elevation Preferred: [50m] Upper: [600m] Lower: [20m]		Space Preferred: [0.25] Upper: [0.55] Lower: [0.01]	
CO2 Preferred: [0.5] Upper: [0.6] Lower: [0.4]		Soil Ph. Preferred: [7] Upper: [10] Lower: [3]	
Soil Depth Preferred: [0.2] Upper: [1] Lower: [0.05]		Ground Cover Preferred: [0.2] Upper: [0.26] Lower: [0.09]	

Figure 50. *Plant Manager* – tolerance/adaptability settings tab

Growth

Growth Info

Maximum Age (Years): Plant Type:

Best Soil Type: ☐ Evergreen

Acceptable Soil Type: ☒ Deciduous

Maximum Height (Metres): ☐ Herbaceous

Canopy (Metres): ☐ Grass

Leaf Density [0,1]:

Reproduction

Reproduction

Reproduction Type: Sexual Maturity Age (Year):

Dispersal Type:

Maximum Seed Count:

Average Germination Percentage:

Pollen Release Date:

Pollen End Date:

Seeding Month:

Germination

Time Element

Germination Days Start:

Germination Days End:

Germination Month Start:

Germination Month End:

Sowing Season:

Environment

Soil Type:

Temperature Lower: [12°C]

Temperature Upper: [24°C]

Moisture Lower: [0.22]

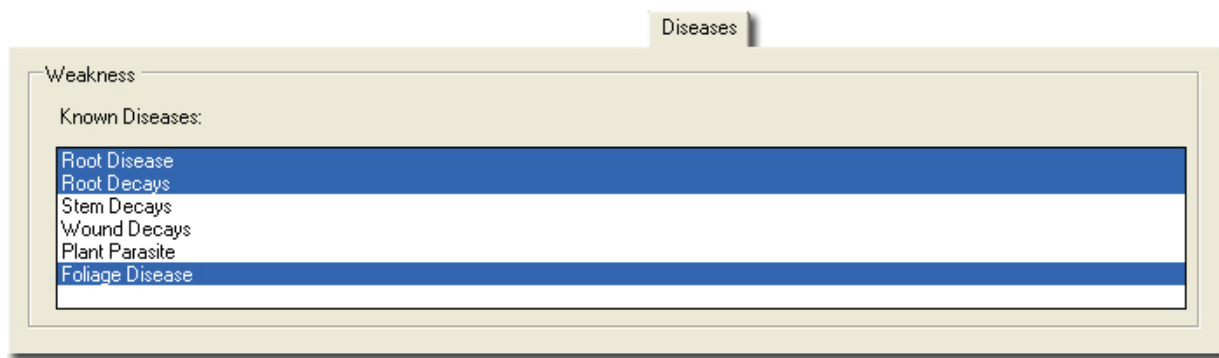
Moisture Upper: [0.6]

Mesh File

Mesh Models

Mesh File (Expired):	<input type="text" value="hazelDead.X"/>	<input type="button" value="Find"/>
Mesh File (Seed):	<input type="text" value="hazelNut.X"/>	<input type="button" value="Find"/>
Mesh File (Seedling):	<input type="text" value="HazelSeedling.X"/>	<input type="button" value="Find"/>
Mesh File (Young):	<input type="text" value="HazelYoung.X"/>	<input type="button" value="Find"/>
Mesh File (Mature):	<input type="text" value="hazelMature.X"/>	<input type="button" value="Find"/>
Mesh File (Old):	<input type="text" value="hazelOld.X"/>	<input type="button" value="Find"/>

Figure 51. *Plant Manager* – Settings tab for Artificial Life-based vegetation

Figure 52. *Plant Manager* – Settings tab for vegetation diseases

4.1.6. SeederEngine User Interfaces

The *SeederEngine* interfaces can be seen in Figure 53 with four screenshots showing the main menu, options menu, ecosystem loading and saving options. The main screens follow that of industry standard interactive games interfaces.

Figure 53. Main screens of the *SeederEngine* environment

The options menu features settings for fog, plant indicator (for indicating plant information), auto screen capture, plant species and dispersal statistics recording, elevation-temperature ratio, and segmentation settings.

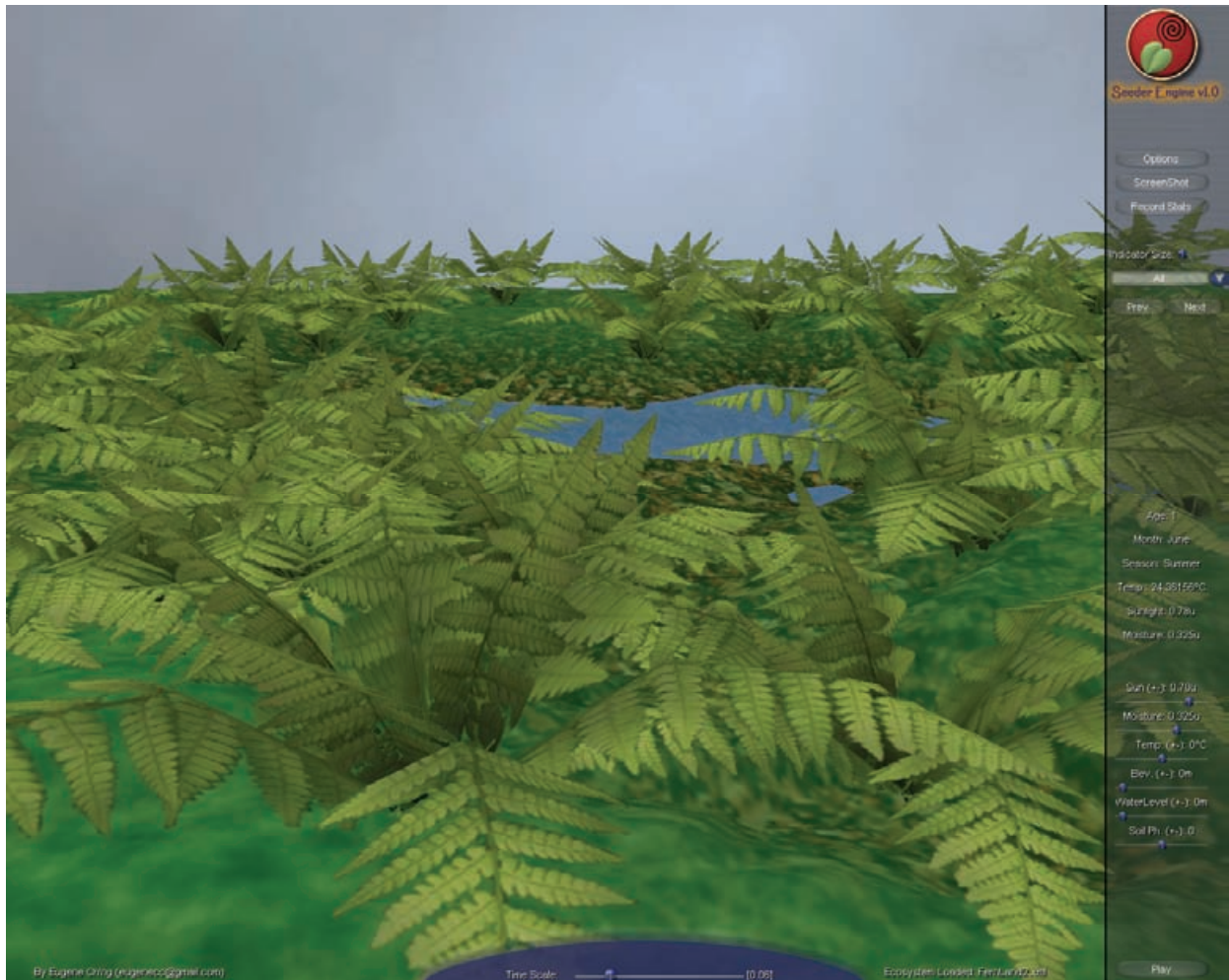


Figure 54. The *SeederEngine* environment

Figure 54 is the simulation interface with the 'FernLand2.xml' ecosystem loaded. The panel on the right (shown in detail in Figure 55) contains buttons for accessing options, taking screenshots, recording statistics, and looping through individual plants and a two state Play/Pause button for controlling the progression of the simulation. The middle section of the panel shows global conditions in the Virtual Environment. At the lower section are real-time environmental adjustments for the increment/decrement of the global levels of sunlight, moisture, temperature, elevation, water level, and soil pH. The track bar at the bottom controls the speed of the simulation. Shortcut keys are shown in Figure 56.

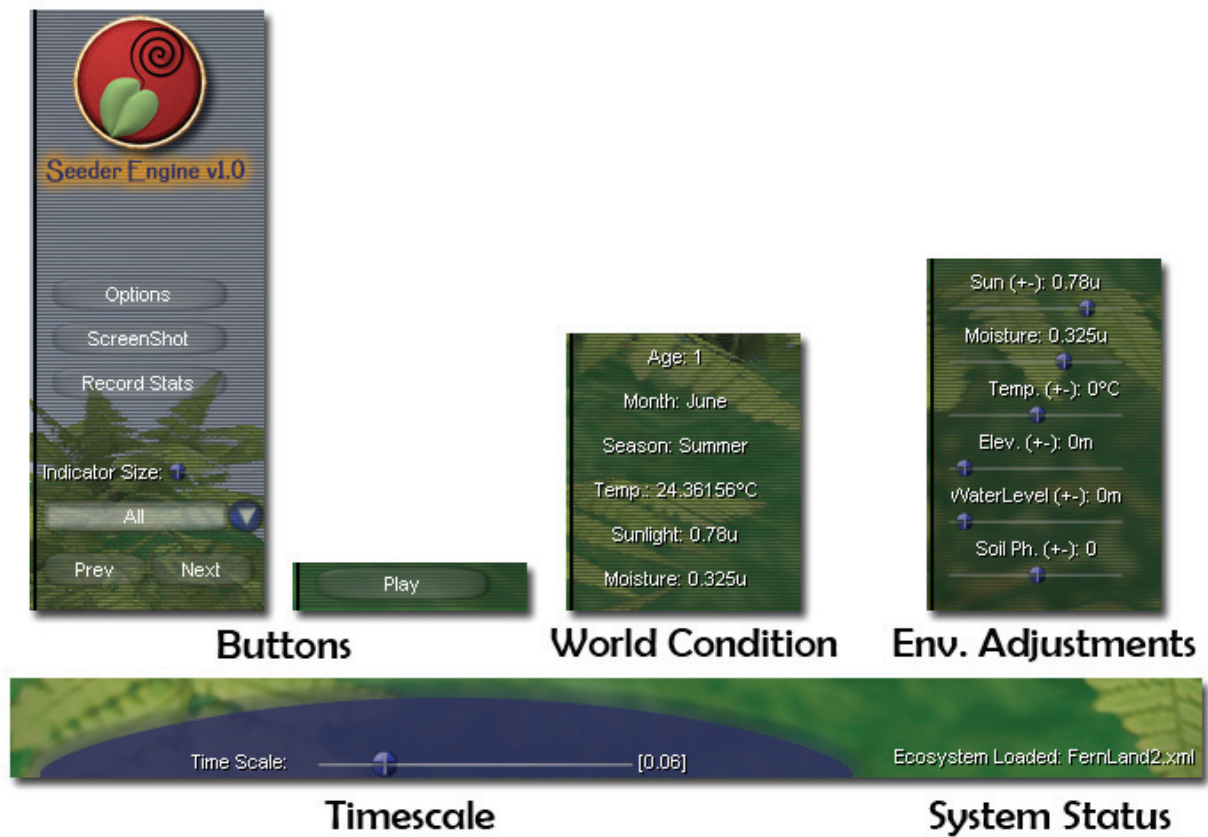
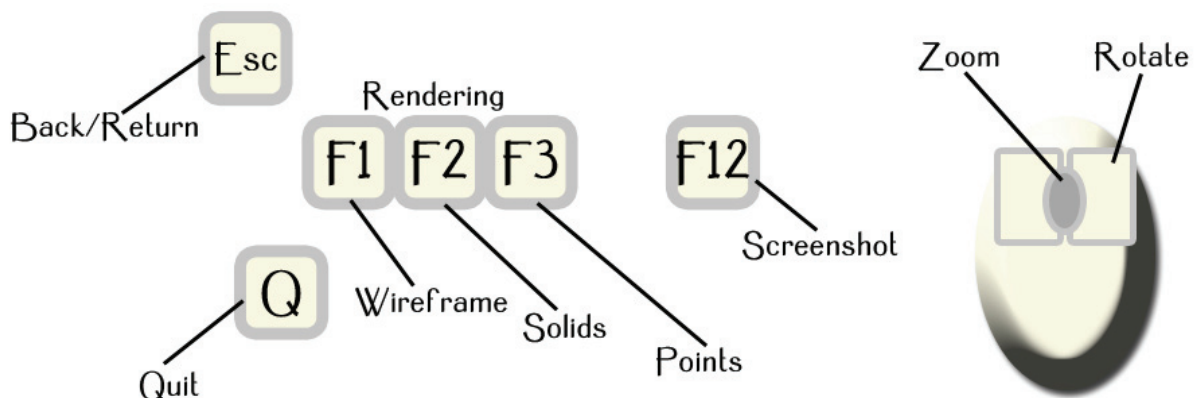
Figure 55. Controls within the *SeederEngine* environmentFigure 56. Shortcut keys in the *SeederEngine* environment

Figure 57 is a screenshot showing plant information in the VE. The individual fitness of plants can be studied via a plant indicator in the Virtual Environment revealing information at the local plant level relating to effective sunlight, nutrient, altitude, soil acidity and so on.

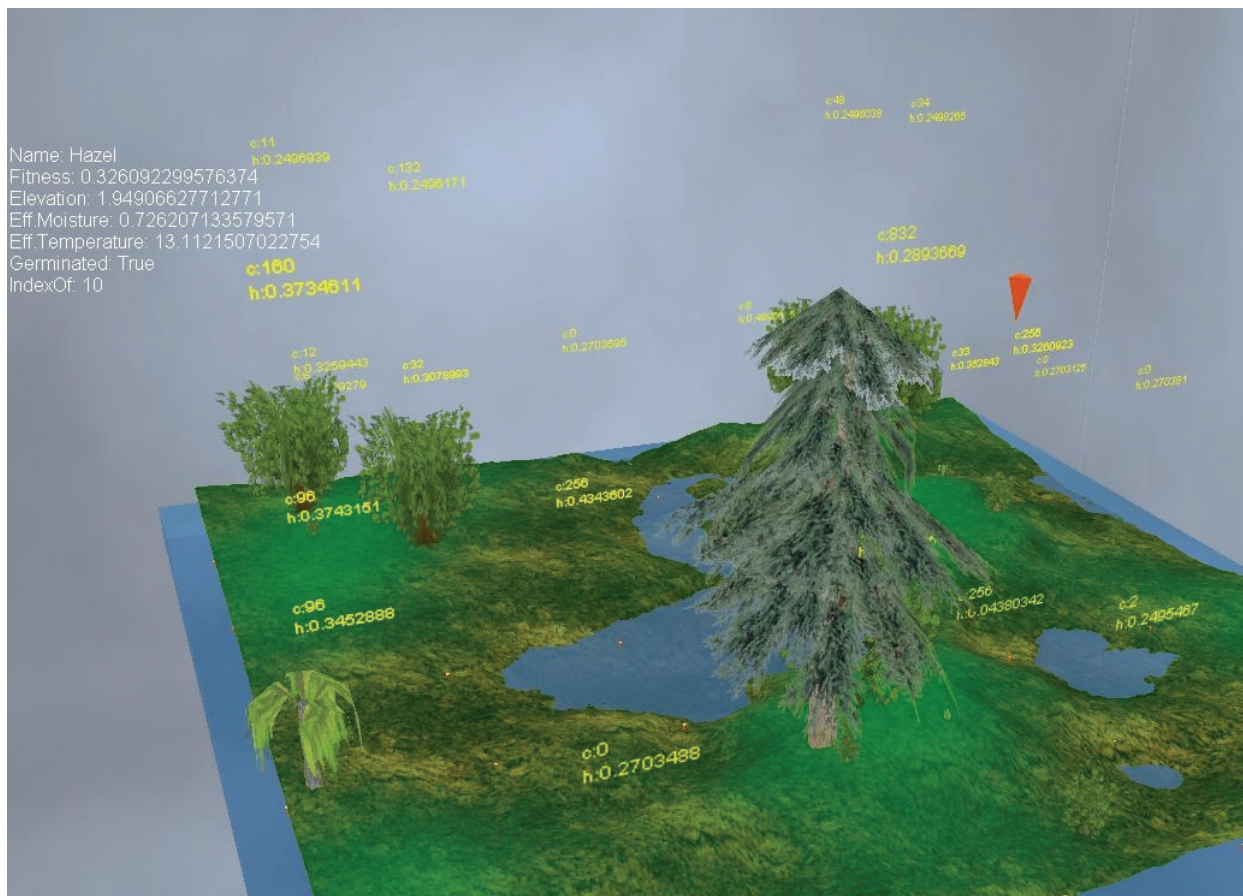


Figure 57. Study view of fitness of individual plants with their local effective conditions

4.1.7. Virtual Environment

Herbert Simon in the *Science of the Artificial* [318] describes a scene where an ant walks along the beach. The complexity of the ant's path, noted Simon, is not necessarily a reflection of the complexity of the ant, but rather, it might reflect the complexity of the beach. The whole point is that the role of the environment is crucial in either influencing or constraining the behaviours of Artificial Life.

The VE in which the plants inhabit is continuous and simulates environmental factors such as sunlight, moisture, temperature (and its variation with altitude), soil conditions, nutrients, and levels of CO₂ present in the atmosphere. Each seasonal change in the virtual world is reflected by the variation in the environmental factors which simulates the climate in the Mesolithic settings. The interactive features in the system allow user control of specific factors such as sunlight, temperature, moisture, global elevation, water level (water logging), and soil acidity. Each factor

can also be disabled from affecting the environment for controlled studies during experiments. By default, virtual time proceeds monthly but can be adjusted to run in days, or weeks. Time is discreet and global bioclimatic parameters are derived from a monthly mean of environmental conditions. As the history of the landscape spans thousands of years, an adjustable timescale feature is included to speed up or slow down the processes for observations of the growing vegetation and plant dispersal patterns.

4.1.8. Ecosystem Blueprint

A typical blueprint of an ecosystem is described below in XML. The migration and temperature variation datasets will be shown in sections 4.2.1 and 4.2.2. Initial plants on the landscape are shown within the *Plants* tag:

```
<Ecosystem>
  <FilePath>
    <TerrainFile>Land20x20.X</TerrainFile>
  </FilePath>
  <Memo>This is a default ecosystem file for SeederEngine.</Memo>
  <Environment>
    <Age>1</Age>
    <Month>June</Month>
    <Season>Summer</Season>
    <SunLight>0</SunLight>
    <Temperature>2</Temperature>
    <Moisture>0.3</Moisture>
    <Elevation>1</Elevation>
    <WaterLevel>3</WaterLevel>
    <SoilPH>2</SoilPH>
  </Environment>
  <GroundInfo>
    <SoilPh>PhField.bmp</SoilPh>
    <SoilDepth>depthField.bmp</SoilDepth>
    <SoilCondition>conditionField.bmp</SoilCondition >
  </GroundInfo>
  <BalanceFactors>
    <Sun>25</Sun>
    <Temperature>25</Temperature>
    <Elevation>25</Elevation>
    <Nutrient>25</Nutrient>
  </BalanceFactors>
  <Migrations />
  <TemperatureVariation />
  <Plants>
    <Plant>
      <PlantXML>Hazel.xml</PlantXML>
      <Life>1</Life>
      <Age>4</Age>
      <PosX>-1370.875</PosX>
      <PosY>56.77783</PosY>
      <PosZ>388.3021</PosZ>
      <Color>-16711681</Color>
    </Plant>
  </Plants>
</Ecosystem>
```

```

</Plant>
<Plant>
  <PlantXML>Pine.xml</PlantXML>
  <Life>1</Life>
  <Age>4</Age>
  <PosX>-1370.875</PosX>
  <PosY>56.77783</PosY>
  <PosZ>388.3021</PosZ>
  <Color>-16711681</Color>
</Plant>
<Plant>
  <PlantXML>Willow.xml</PlantXML>
  <Life>1</Life>
  <Age>4</Age>
  <PosX>-1370.875</PosX>
  <PosY>56.77783</PosY>
  <PosZ>388.3021</PosZ>
  <Color>-16711681</Color>
</Plant>
</Plants>
</Ecosystem>

```

4.2. SeederEngine Implementation Techniques

Implementation techniques in DirectX for the real-time engine is similar to methods used in the industry and need not be covered. However, specific techniques developed in this research will be elaborated. In particular, a system that is built for simulating large spatial-temporal models requires special design. This section covers the technical aspects of the implementation.

4.2.1. Environmental Variations

Environmental factors such as sunlight, temperature, moisture, and carbon dioxide are complex, varies across time, and are affected by many other factors. These variations can be simulated by giving a probability of slight increment/decrement of value over known Mesolithic environmental factors. The algorithm below shows the method.

Listing 1:

```

1. Receive parameter pFactor
2. If probability within p
3.   Increment pFactor by value from 0 to v
4. Else
5.   Decrement pFactor by value from 0 to v
6. Adjust pFactor so that it does not exceed the minimum/maximum value
7. Return pFactor

```

The algorithm receives an environmental factor $pFactor$ and determines the variation v based on a user-specified probability $p=[0,1]$ which increments $pFactor$ by v , another value specified by the user. A higher value of p (>0.5) increases the frequency of incremental $pFactor$. Later, $pFactor$ is adjusted so that it does not exceed the value. For example, the moisture content uses a unit $[0,1]$, and $pFactor$ is adjusted so that it does not exceed the minimum or maximum unit.

4.2.2. Large Timescale Temperature Variation

Temperature variation over large timescale is an important factor for species competition. The algorithm simulating temperature variation resides within the *Environment* class and is described in the ecosystem XML blueprint below.

```
<TemperatureVariation>
  <Set>
    <TemperatureChange>1.7</TemperatureChange>
    <YearsOfChange>100</YearsOfChange>
  </Set>
  <Set>
    <TemperatureChange>1.7</TemperatureChange>
    <YearsOfChange>100</YearsOfChange>
  </Set>
  <Set>
    <TemperatureChange>-1.7</TemperatureChange>
    <YearsOfChange>100</YearsOfChange>
  </Set>
  <Set>
    <TemperatureChange>1.7</TemperatureChange>
    <YearsOfChange>100</YearsOfChange>
  </Set>
</TemperatureVariation>
```

Each set is a time slot containing the year and the temperature change. Each subsequent sets describe the year in addition to the previous year in the set. In the first set the temperature increases by $+1.7^{\circ}\text{C}$ from year 0-100; subsequently the second set increases by $+1.7^{\circ}\text{C}$ from year 100-200, therefore, the temperature in the year 200 is increased by $+3.4^{\circ}\text{C}$. The third set shows a decrement of -1.7°C over the next 100 years. The temperature change per month T_{month} for the subsequent year of change is thus,

$$T_{month} = \frac{T_{change}}{Y_{next}} 12^{-1}$$

where T_{change} is the temperature change, Y_{next} is the subsequent years of change. The algorithm for generating the temperature change is as follows:

Listing 2:

1. *Start: Retrieve temperature variation dataset from XML*
2. *On Update:*
3. *World temperature + T_{month}*
4. *For each dataset*
5. *Skip code if dataset is empty or if the current variation year has not passed*
6. *Compute temperature variation for the next year of change*
7. *Next*

4.2.3. Migration

Migration is part of the factors affecting an ecosystem in vegetation succession models. The algorithm simulating migration resides within the *ALIFE* class. The migration dataset described in the *Ecosystem* blueprint is:

```
<Migrations>
  <Set>
    <AgeOfMigration>200</AgeOfMigration>
    <PlantType>Hazel.xml</PlantType>
    <NumberOfPlant>40</NumberOfPlant>
    <PlantAge>2</PlantAge>
  </Set>
  <Set>
    <AgeOfMigration>400</AgeOfMigration>
    <PlantType>Elm.xml</PlantType>
    <NumberOfPlant>40</NumberOfPlant>
    <PlantAge>1</PlantAge>
  </Set>
  <Set>
    <AgeOfMigration>500</AgeOfMigration>
    <PlantType>Oak.xml</PlantType>
    <NumberOfPlant>40</NumberOfPlant>
    <PlantAge>0</PlantAge>
  </Set>
</Migrations>
```

Each set contains the year of species arrival, the species, the number of plants arriving on the landscape, and the age of the migrating plants. The sets showed that at year 200, Hazel arrive on the landscape. Subsequently, Elm arrives at year 400, and at year 500 Oak arrives. It is possible to set the age of migration as yearly. The number of plants that may eventually reach the landscape varies even though a specific value is specified in each set. This is due to the fact that the virtual landscape has a set boundary, and plants scattered outside the boundary are removed from the

system. The conditions of the soil on which the plants arrive in will also affect its health, causing some plants to die. If the age of the plant is set to 0, seeds will be distributed instead of plants. The algorithm for plant migration is shown below.

Listing 3:

```

1. Start: Retrieve migration dataset from XML
2. On Update:
3.   For each dataset
4.     If the age matches the dataset
5.       Compute migration and distribute plants onto the terrain
6.     Next

```

4.2.4. Ground Info

Ground Info defines local soil and ground conditions on a terrain. SeederEngine supports three ground infos – soil acidity, soil depth, and ground condition but can be extended to include other topology related conditions that can be described by height fields. Height fields are greyscale bitmaps with 256 levels (0-255). The concept is simple (Figure 58), a higher number from the scale yields a higher concentration of certain conditions. White (255) is the peak and black (0) is zero concentration. The scales can denote any conditions that can be numerically represented. For example, soil acidity or pH level is between pH 0.0 (acidic) to pH 14.0 (alkaline) with pH 7.0 as neutral. The greyscale values can be normalised ($g_{normalised}$) and multiplied by the pH numerical value to yield C_{actual} , the actual condition of the soil normalised from the greyscale,

$$g_{normalised} = \frac{g_{level}}{g_{peak}}$$

$$C_{actual} = C_{peak} g_{normalised}$$

Where $g_{level} = [0, 255]$ is the level of greyscale representing the current ground condition, $g_{peak} = 255$ is the peak of the greyscale level and C_{peak} is the peak numerical value of the soil. In the case of soil acidity, C_{peak} is pH 14.0.

In soil depth for example, $g_{normalised}$ can be 1.0 representing a negative condition – impenetrable soils. For very shallow soils $g_{normalised}$ can be 0.9.

Ground condition can represent any situation where specific study related to it is needed. For example, it can represent terrains with harsh textures, soil inflexibility, or a topological slope. A value of $g_{normalised} = 1.0$ can represent a large rocky surface while $g_{normalised} = 0.0$ represents a very flexible soil type. For topological slope, $g_{normalised} = 0.5$ represents a 45° angle, a value of 1.0 represents a 90° slope, and 0.0 represents a flat surface. We shall see later that for $g_{normalised} = [0,1]$, the value had to be inversed $1 - g_{normalised}$ for the vegetation fitness function model. The fitness of the plant towards the soil and topological condition is determined by its adaptability towards these conditions. The technique for modelling plant adaptability is developed in section 4.3.8.

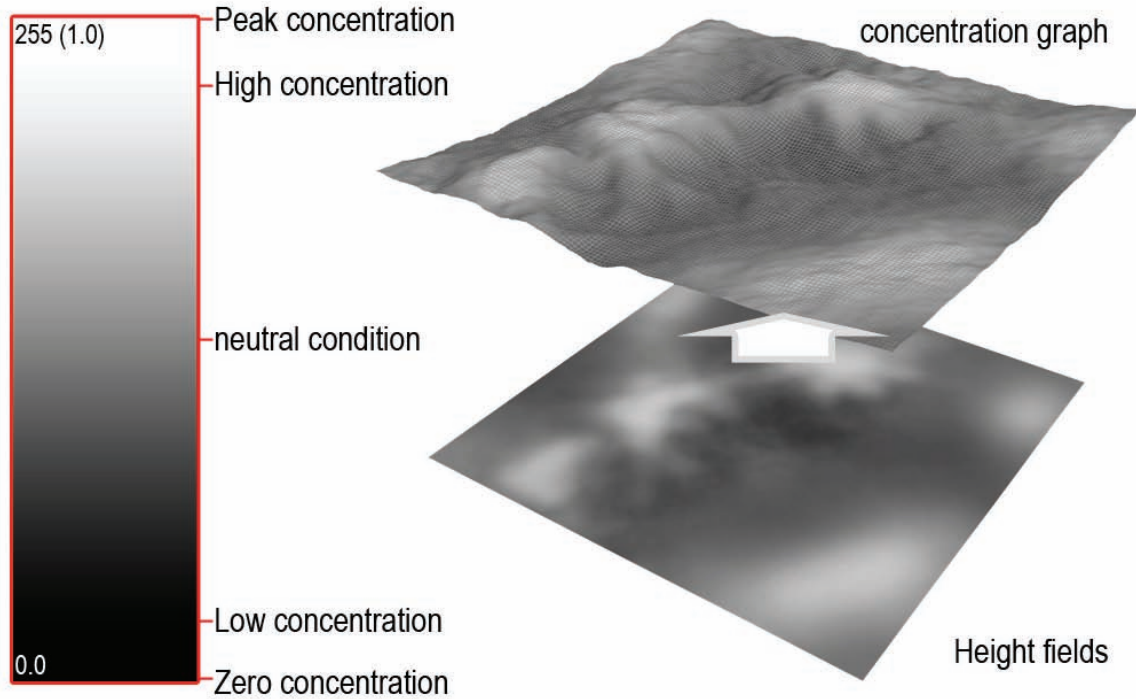


Figure 58. Greyscale height fields representing various soil conditions

An efficient technique has been developed in this research for mapping height fields onto the terrain for simulating local ground conditions accessible by vegetations. There are two ways for mapping height fields onto the terrain:

1. Apply the height fields as textures onto the terrain and read from the location the vegetation is at.
2. Load the height fields separately from the terrain and mapping the terrain-height field ratio for reading the values.

The second approach is more efficient as accessing textures mapped onto the terrain requires computing resources for intersecting terrain geometries. The approach (Figure 59) maps the location of vegetation to the ground condition by computing the ratio between each height fields and the terrain with,

$$R_x = P_x \frac{w_b}{w_t}, R_y = P_y \frac{h_b}{h_t}$$

Where $R_{x,y}$ is the mapped ratio from the terrain to the height field, $P_{x,y}$ is the location of a plant on the terrain, w_b and h_b is respectively the width and height of the height field, w_t and h_t is respectively the width and height of the terrain, if seen from a top view on the screen.

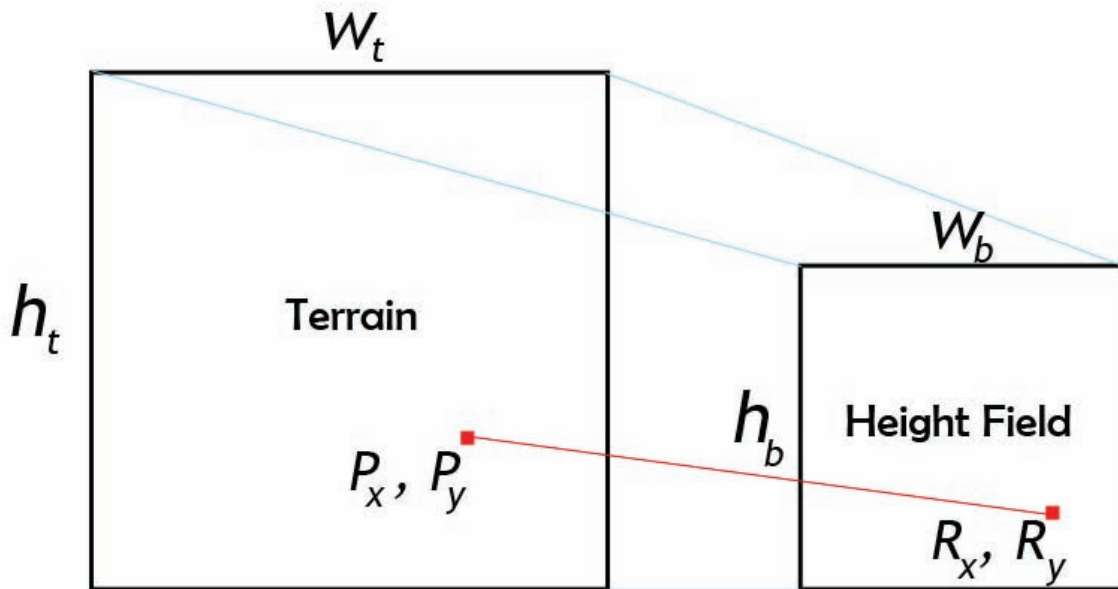


Figure 59. Mapping terrain-height field ratio for accessing ground info

4.2.5. Segmentation

The segmentation algorithm presented here is an optimisation technique developed and experimented in this research. In an alife environment, there are bound to be large numbers of alife entities interacting with other entities, both accessing and competing for resources. The segmentation of the Virtual Environment will determine the computational speed in the simulation of large numbers of alife entities. The large number of entities are usually stored in a single array, and if the programming language is object-oriented, the entities are stored using a *collection* object. In each update of the main class, each entity accesses every other entity in the same collection to determine their proximities for interaction or competition. If an entity is able to ‘see’ another entity due to its proximity, interaction occurs. Therefore, if the collection contains ten entities, each entity will have to go through ten loops including itself for it to determine which other entity are at proximity before computing the interaction. This amounts to $10^2 = 100$, and if there are 1000 entities, the amount increases tremendously at $1000^2 = 1,000,000$. In a large landscape, the vegetation could easily amount to thousands to hundreds of thousands of plants. This inefficiency in computation gives reason for researching new optimisation techniques. In the initial stages of research, three techniques were studied.

The first technique requires that each entity remembers the indices of nearby entities (Figure 60a). In this technique, each entity accesses only the indices in its memory for interaction and competition. The technique however, has its limitations. We know that vegetation reproduces abundantly during the spring-summer seasons each year. In the Virtual Environment, each time new plants are reproduced plant proximities in the entire collection will have to be traversed and computed to determine which plants should be in the memory of which other plants. And each time a single plant dies the collection has to be traversed again to remove the index of the dead plant from the memory of nearby plants. This becomes very slow as the large number of plants increase.

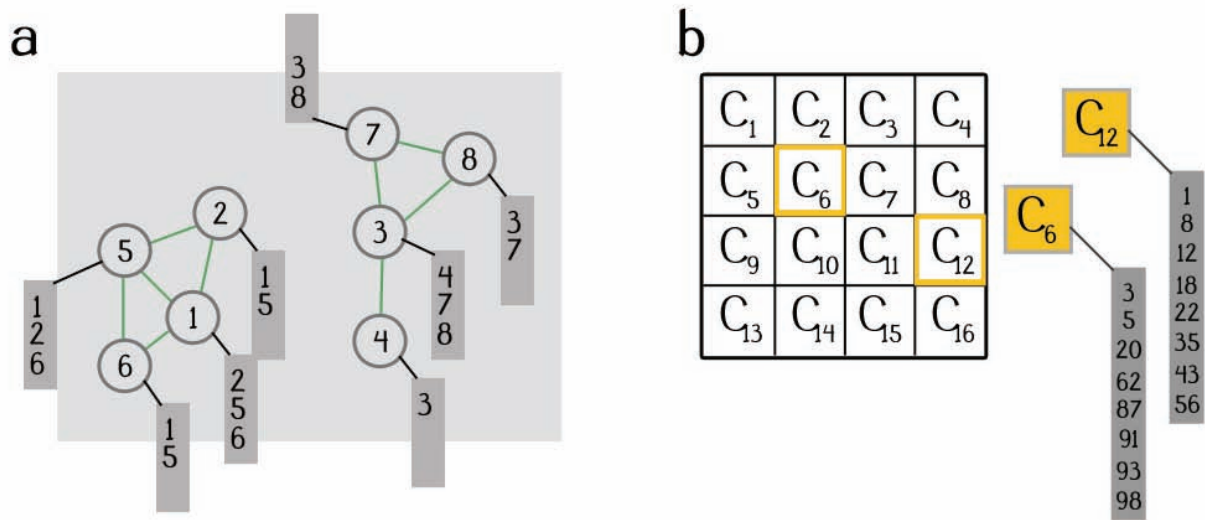


Figure 60. Considerations for two index optimisation techniques developed in the research. These are not used due to its inefficiency in comparison to the third technique

The second technique segments the landscape into different collection classes storing the indices of alive entities in each class (Figure 60b). This is a better algorithm compared to the first since the segments in a terrain is fixed provided the landscape is not continually being re-segmented during the simulation. However, different collection classes increases memory and the need to traverse each collection during simulation wastes CPU time. Besides, in each reproductive lifecycle, each collection has to be checked against the new plants to determine which segment boundary it belongs to.

The third technique is used throughout the research as it is far more efficient. In a landscape, a plant can only compete with adjacent plants at a given time and all other plants should be discounted from the interaction.

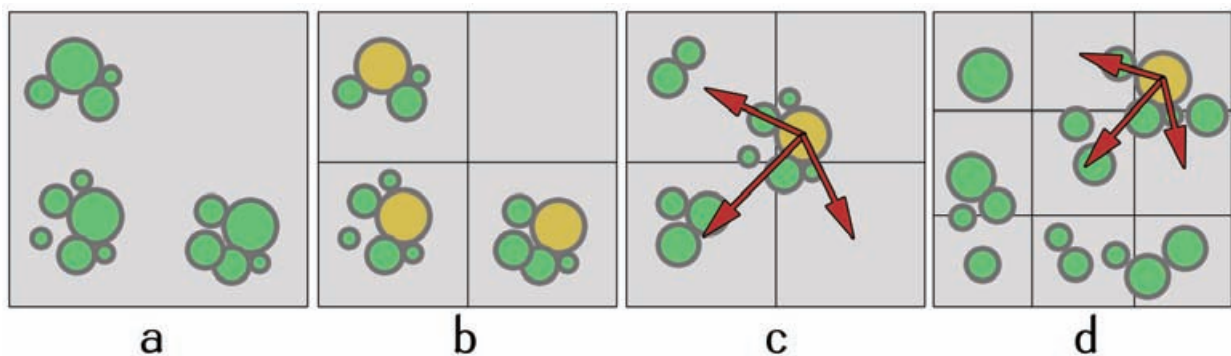


Figure 61. Concept of segmentation

Figure 61a shows a landscape with groups of plants where only intersecting plants are being competed against. In the real world, computation is not a problem since interaction between entities is parallel and occurs simultaneously. However, since every virtual plant is stored within an array in a computer program, traversal is required to determine which plant is ‘visible’ for competition. In the virtual world, the ideal competition situation for segmentation in Figure 61a can be divided into 4 segments where each plant needs only access the other plants in its own segment space shown in *b*. In a difficult segmentation condition at *c* where the source plant (orange) is near to a boundary or overlaps the boundary of a segment space, the source plant requires accessing all other plants in every other segment space adjacent to its own. In this case, the benefits of segmenting the landscape are not apparent as it is the same as condition *a* since all plants within the array is accessed. The benefits become apparent when the segments are increased in *d*. The figure illustrates that a higher segmentation increases the speed of the program since each plant needs only access the plants within its segment space and adjacent segment spaces. The only rule needed is that the size of a segment should not be smaller than the canopy of a tree with the largest diameter.

Segmenting a landscape in a standard DirectX or OpenGL 3D coordinates is different from the 2D screen coordinate systems. The method developed in this research targets the 3D coordinate space but can be easily extended to include its 2D version. Segmentation begins with divisions. The number of divisions can be from 1 to ∞ subject to the limits of computer memory. The segments are derived from the square of the divisions with $d = \sqrt{d^2} = \sqrt{S}$, where d is the number of divisions and S is the number of segments. Figure 61a contains 0 or 1 division with 1 segment, $1 = \sqrt{1^2} = \sqrt{1}$. The landscape in *b* and *c* both contains 2 divisions with 4 segments, $2 = \sqrt{2^2} = \sqrt{4}$. Landscape *d* contains 3 divisions with 9 segments $3 = \sqrt{3^2} = \sqrt{9}$. The number of divisions are equal between the width and height of a landscape and the value of the width and height of the landscape can be obtained with,

$$w_{divs} = \frac{w_{terrain}}{\sqrt{S}}$$

$$h_{divs} = \frac{h_{terrain}}{\sqrt{S}}$$

where w_{divs} and h_{divs} are both respectively the number of divisions in the width and height of the terrain. $w_{terrain}$ and $h_{terrain}$ are the size of the width and height of the terrain. \sqrt{S} is the number of divisions which divides the terrain into w_{divs} and h_{divs} .

Constructing the segments requires an understanding of the 3D coordinate system, shown in Figure 62a. The origin of the axis lies at the centre of the plane with extensions of the axis in both the negative and positive directions. The segmentation however, cannot begin from the origin but is offset in the negative $(-x, -y)$ direction starting from the ‘start’ position shown in *b*. This means that segment 0 begins from the lower left corner $(-x, -y)$ and ends at the top right corner $(+x, +y)$ at segment 15. The units $(-50, -25, 0, +25, +50)$ are given as an example and can be replaced with any other units with equal divisions. Based on the divisions of width at *b*, it is observed that when $j=0$, $x=-50$, when $j=1$, $x=-25$, when $j=2$, $x=0$, and so on. This generates a graph at *c* where an equation of the line is given,

$$f(j) = j \frac{w_{terrain}}{\sqrt{S}} - \frac{w_{terrain}}{2}$$

where j is the segment junction, $w_{terrain}$ is the width of the terrain, and \sqrt{S} is the number of divisions. The equation offsets the first segment (0) from the origin to the ‘start’ position. A construction of the height divisions uses the same equation replacing $w_{terrain}$ with $h_{terrain}$.

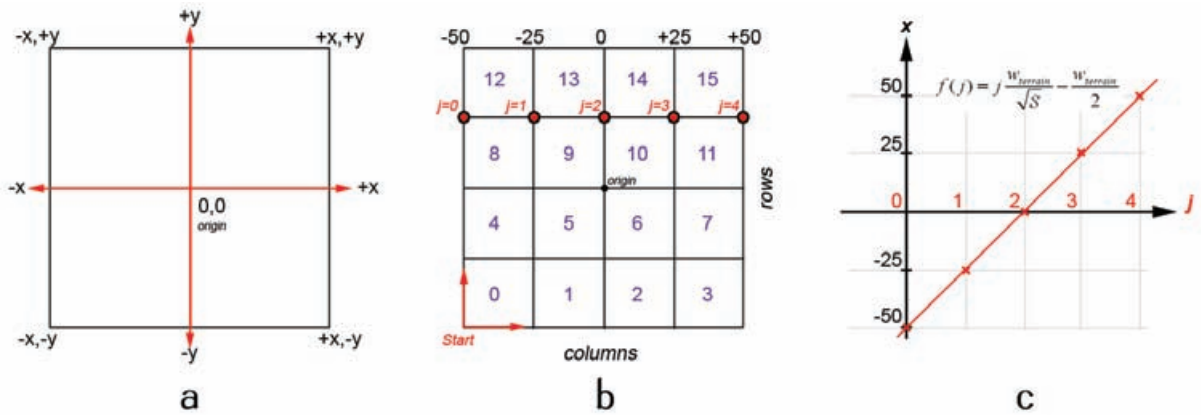


Figure 62. Segmentation constructions in 3D coordinate space

In the algorithm, each segment is a rectangle object storing its size and position. The C# algorithm is given below. *divs* is the number of divisions, *i* and *j* are each division's index, *wDiv* and *hDiv* are the width and length of each segment divided from $\frac{w_{terrain}}{\sqrt{S}}$ and $\frac{h_{terrain}}{\sqrt{S}}$.

Listing 4:

```

1. int n = 0; // segment number
2. for (int j = 0; j < divs; j++) // Rows (divided on Length)
3. {
4.     for (int i = 0; i < divs; i++) // Columns (divided on Width)
5.     {
6.         x = (terrainWidth/divs)*i - terrainWidth/2; // Set the x position (Columns)
7.         y = (terrainHeight/divs)*j - terrainHeight/2; // Set the y position (Rows)
8.
9.         // Create a new segment
10.        segment[n] = new Segment(x*2, y*2, wDiv*2, hDiv*2);
11.        n += 1; // next segment
12.    }
13.}

```

Every plant in its own segment space accesses its adjacent segment spaces. Figure 63a shows the index accessing pattern using a one dimensional array. *T* is the target segment where a plant resides. The plant accesses its adjacent segment spaces for competition. The segmentation in *b* shows black coloured segments within the safe frame (red). In *c*, the segment within the safe frame (blue arrows) safely accesses segments that exist whereas segments outside the safe frame (red arrows) accesses non-existent segments and will generate errors in the program.

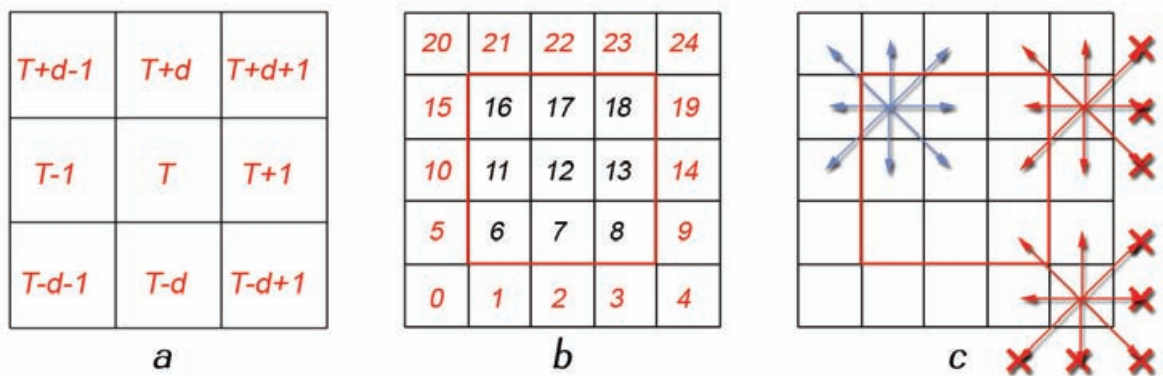


Figure 63. Segmentation safe frame

This problem can be solved by preventing the left edge and corner segments from accessing certain non-existing segments. Figure 64 shows some instances of the patterns of non-existent segments where the target segment should not have access to. The pattern illustrates that depending on where the edge segment (orange) is located (top, bottom, left, right), it should not access not less or more than three non-existent segments. The corner segments should not access not less or more than 5 non-existent segments. The algorithm for segregating the edge and corner segments is given below.

Listing 5:

```

1. // Collect Segment Corners
2. pBottomLeftCorner = 0;
3. pBottomRightCorner = pDivisions-1;
4. pTopLeftCorner = pDivisions * (pDivisions-1);
5. pTopRightCorner = pNumOfSegment-1;
6.
7. // Collect Segment Edges
8. pLeftEdge = new int[pDivisions-2];
9. pRightEdge = new int[pDivisions-2];
10.
11. for (int i=0 ; i < pDivisions-2 ; i++)
12. {
13.   pLeftEdge[i] = (i+1) * pDivisions;
14.   pRightEdge[i] = (pDivisions-1) + pDivisions * (i+1);
15. }
```

pDivisions is the number of divisions on the landscape, *pNumOfSegment* is the number of segments on the landscape. The rest are self-explanatory.

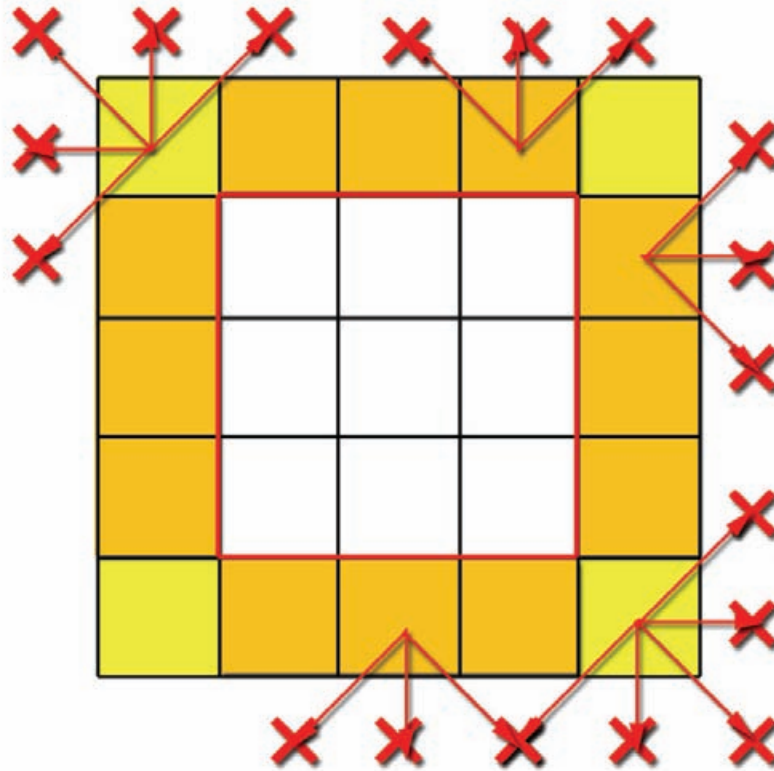


Figure 64. Segmentation safe access

A UML diagram showing the class relationship between the *Segment* and *Vegetation* is given in Figure 65. Every plant has a unique *VegetationID*. Within the plant, *SegmentID* defines the segment the plant is in and has a default value of -1 when it is in the seed stage. It is assigned when the seed is germinated as that is the beginning of competition. The *Segment* object contains a unique *SegmentID* and an array of *PlantIndices[]* which stores the index of each plant within the boundary of the segment rectangle. The index of a plant can only be in the *PlantIndices[]* array of one segment at any given time.



Figure 65. The relationship between Vegetation and Segment

4.2.6. Segmentation Results

Statistics of the optimisation technique covered in the previous section were recorded on a landscape 150m² with five species of trees on the landscape. The total number of trees is 147 distributed among the species. The environmental conditions were set to harsh so that it is more competitive. This is predicted to show a more interesting trend of population in the study.

The three segmentation experiments were conducted to compare the results using the same settings where vegetation reproduces up to a maximum of 162 on one of the experiment. The first segmentation test uses 1 segment for the landscape with a total of 162 at peak production over 258 years, the second and third partitioned the terrain into 64 and 144 segments respectively. The 64 segments version produces 147 plants at its peak over 263 years and the 144 segments version produces up to 151 during its peak over 258 years. Even though the settings are the same for all three experiments, the number of vegetation produced is different. This is due to the interaction among vegetation and the environmental variations affecting them. This however, does not significantly affect the results as comparison is made between the speed and the number of plants produced (Figure 66-Figure 68).

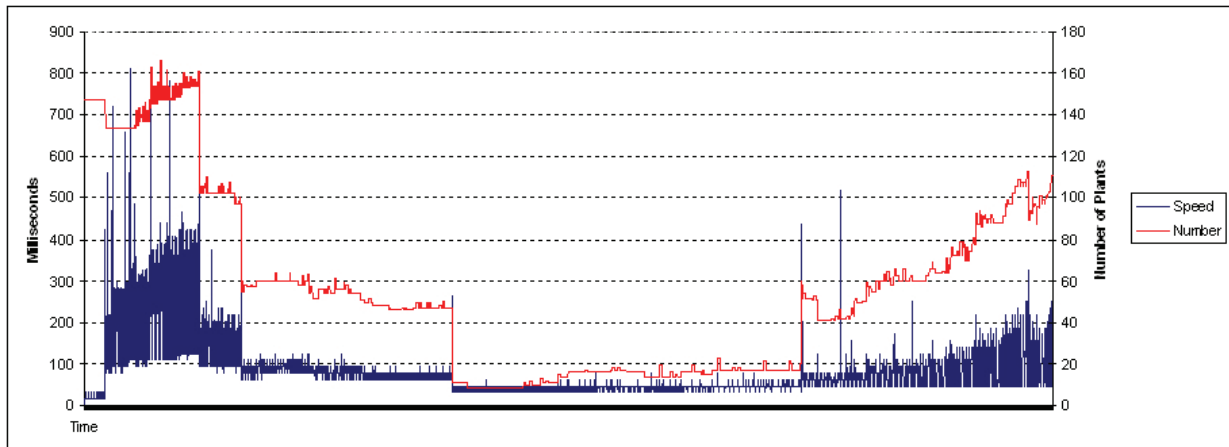


Figure 66. Experimental results using 1 segment on the landscape

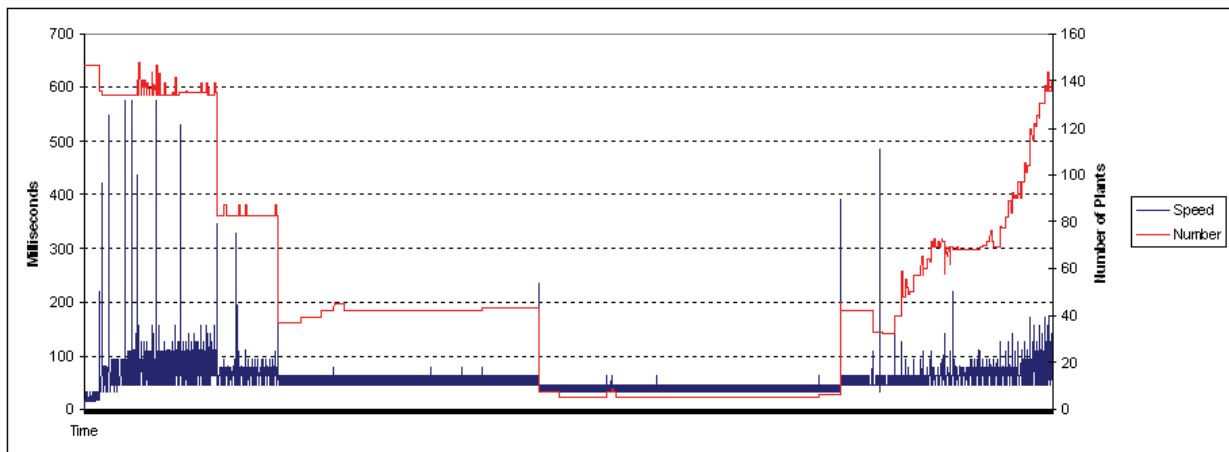


Figure 67. Experimental results using 64 segments on the landscape

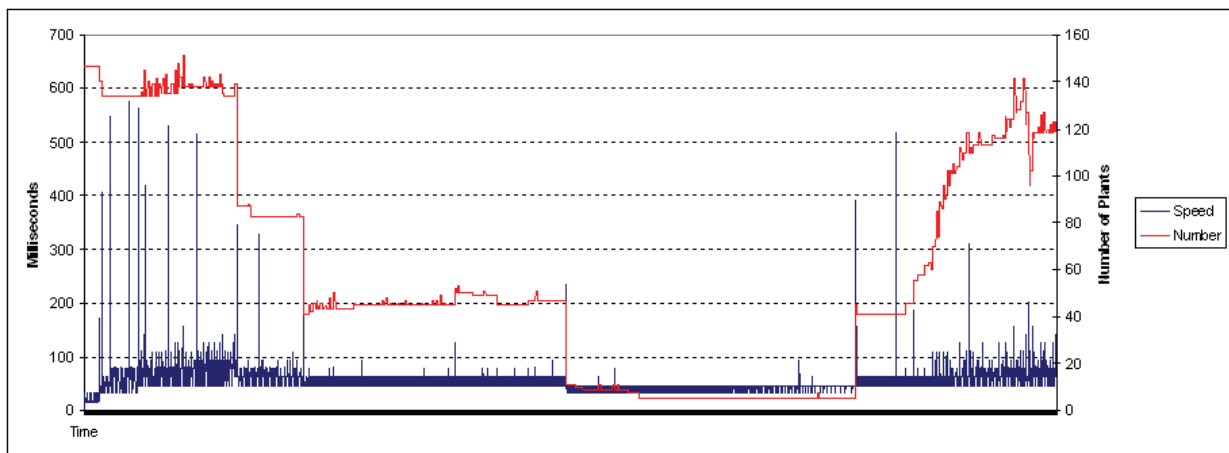


Figure 68. Experimental results using 144 segments on the landscape

A comparison of the three graphs showed that there are significant increase of speed if the segmentation algorithm is applied. In Figure 67, when the number of vegetation reaches its maximum at over 140, the speed reaches only 180 milliseconds using 64 segments as compared to an average of 400 milliseconds using only 1 segment (Figure 66). If the segments are increased to 144, the speed decreased to only an average of 100 milliseconds with the same amount of vegetation (Figure 68).

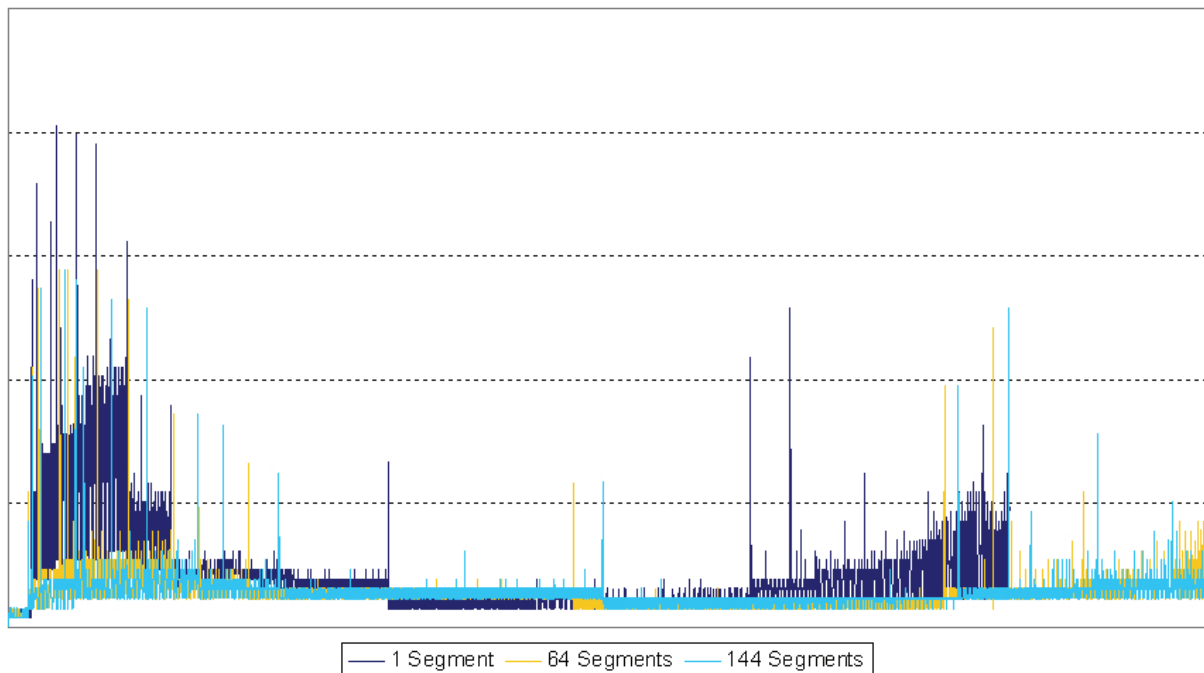


Figure 69. The comparison of speed between the segmentation experiments

Figure 69 is a comparison of speed between the three segmentation experiments. The graph showed that the computational speed increases significantly between 1 and 64 segments. However, the increase in performance is not apparent between 64 and 144 segments. This is due to the small number of vegetation present in the landscape. The performance becomes obvious when the number of vegetation is greatly increased. Figure 70 and Figure 71 are graphs comparing segmentation results of a habitable environment using the same landscape. Vegetation is a mixture of trees and herbaceous plants totalling 203 in number at the start of the simulation. The herbaceous plants are used because its rate of reproduction is much faster than the trees. The 64 segments version produces 14,795 plants at its peak over 23 years and the 144 segments version produces up to 12,393 during its peak over 33 years. The comparison shows a significant increase in performance using 144 segments. When the number of plants increases to around 12,000 (Figure 71), the speed decreases to only 300,000 milliseconds as compared to the 64 segments version at 700,000 milliseconds.

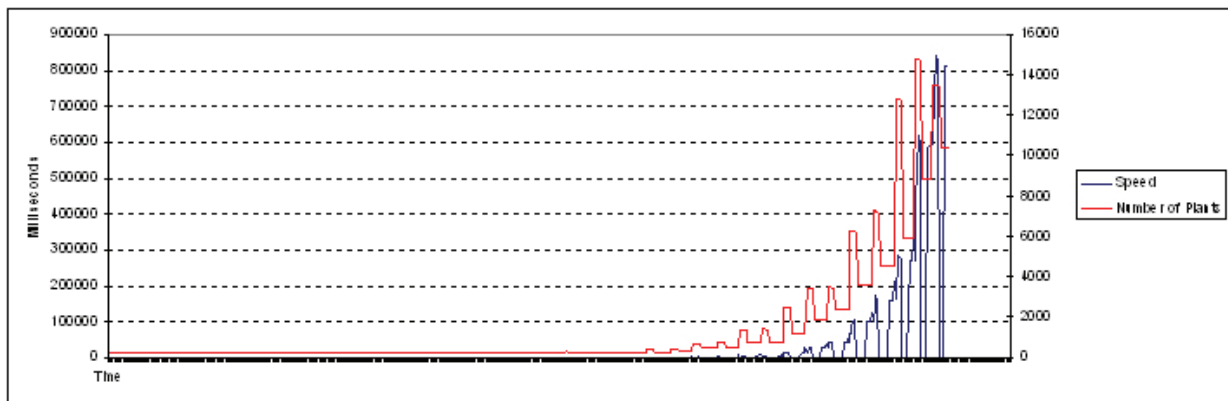


Figure 70. The comparison of speed between the segmentation experiments

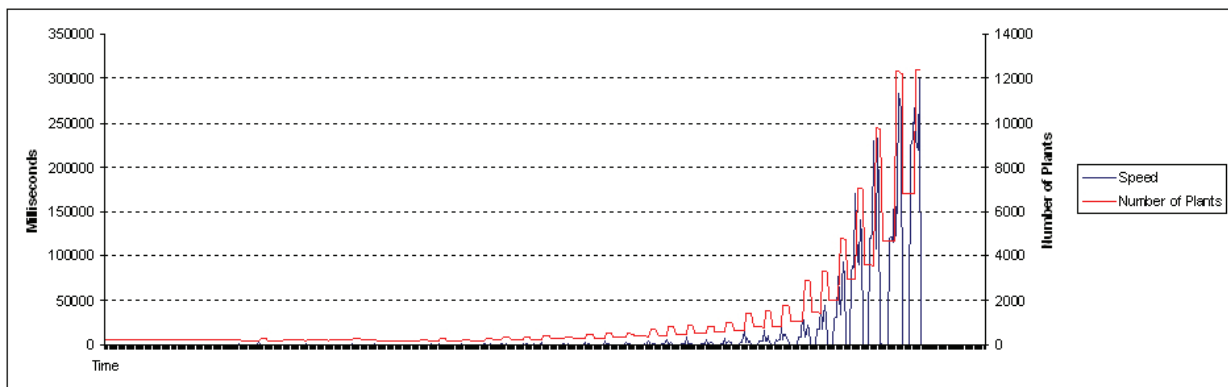


Figure 71. The comparison of speed between the segmentation experiments

4.2.7. Plant Species and Dispersal Statistics

The statistics of plant species and dispersal patterns can be recorded by dividing the terrain into elevation layers and counting the number of species in each layer. Figure 72 illustrates the concept.

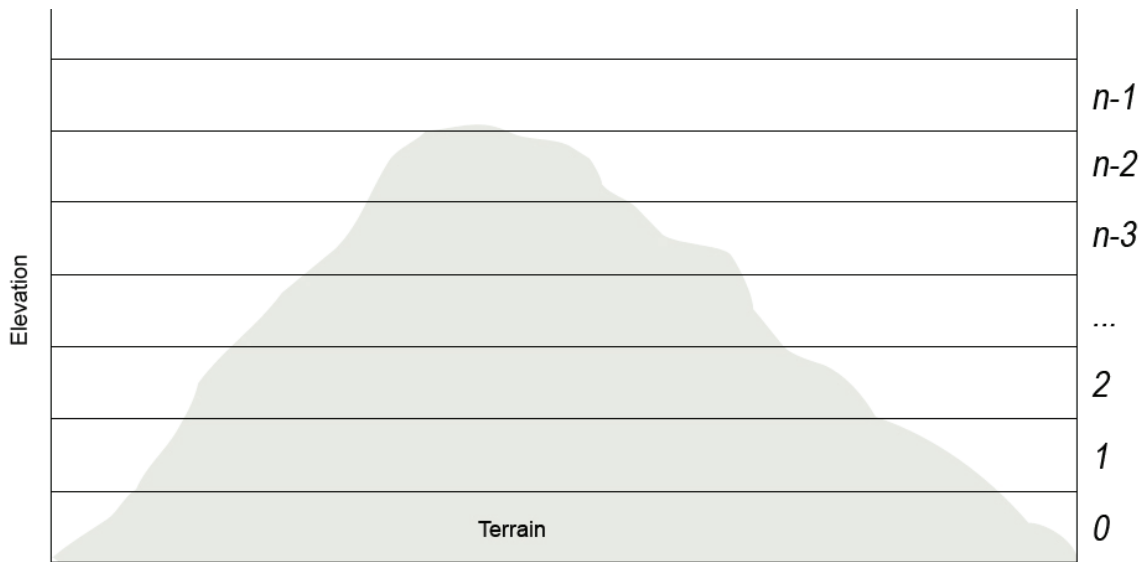


Figure 72. Elevation layers for determining species distribution

4.3. Techniques for Synthesising Vegetation

Since Turing's work on the power of self-assembly [319], years of laborious investigations by a handful of individuals have revolutionised the way we think about the world and its systems. The paradigm shift from recognising physical systems as constrained by centrality to one that works via the interaction of distributed components has initiated new terrains for multidisciplinary research.

According to the bottom-up methodology in alife, an approach for modelling vegetation could begin from the cell level (Figure 73a), with interacting cells forming the smaller components of a tree, and the smaller components forming the vascular systems (Figure 73b) which structure eventually complete the tree. Another way is to model the vascular structure of a tree (Figure 73b) with its root and shoot system interacting with itself, the environment, and other plants to form a tree that is limited by its pattern architecture (species). Each of these approaches may be useful for

certain studies, however, considering the limitations of computing resources and the specific problem domains the research presented here is attempting to solve, in order to determine vegetation dispersal patterns on large terrains, modelling vegetation as complete entities (Figure 73c) that respond to ecological factors, availability of resources, and threats from competition and the environment may be a more feasible approach.

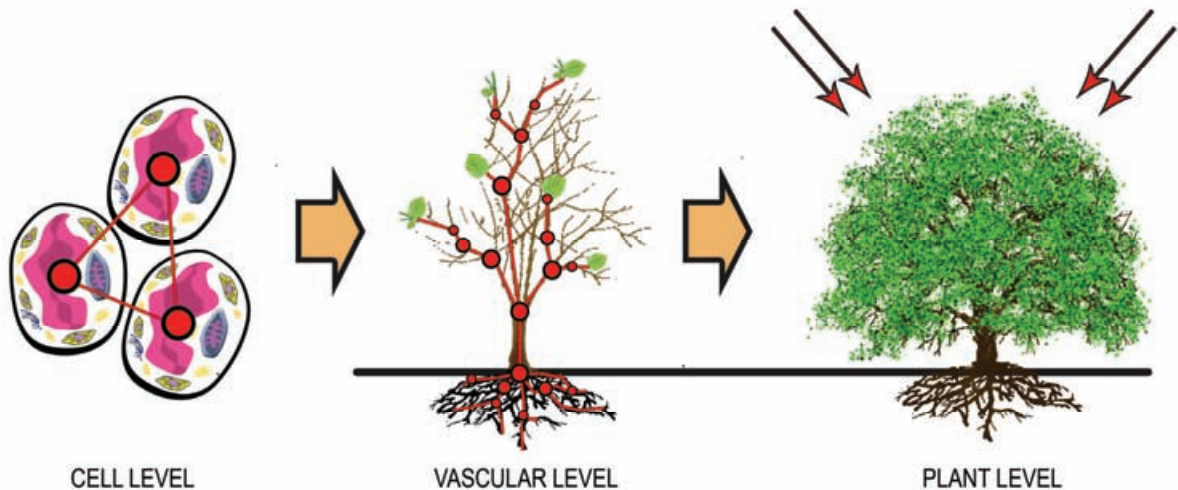


Figure 73. Vegetation modelling techniques

Learning from examples in living systems, we could perceive landscapes as large organisms composed of many decentralised entities (species of vegetation) which collectively form and replenish the larger systems (the earth) by forming patterns of forests and colonies by relying on the availability of resources and the suitability of the ecology on the ecosystem (Figure 74). In accordance with the concept of emergence, the local interaction of these vegetation communities in addition to ecological variables should appropriately synthesise the formation of vegetation communities on niches of each species' ecology on terrains.

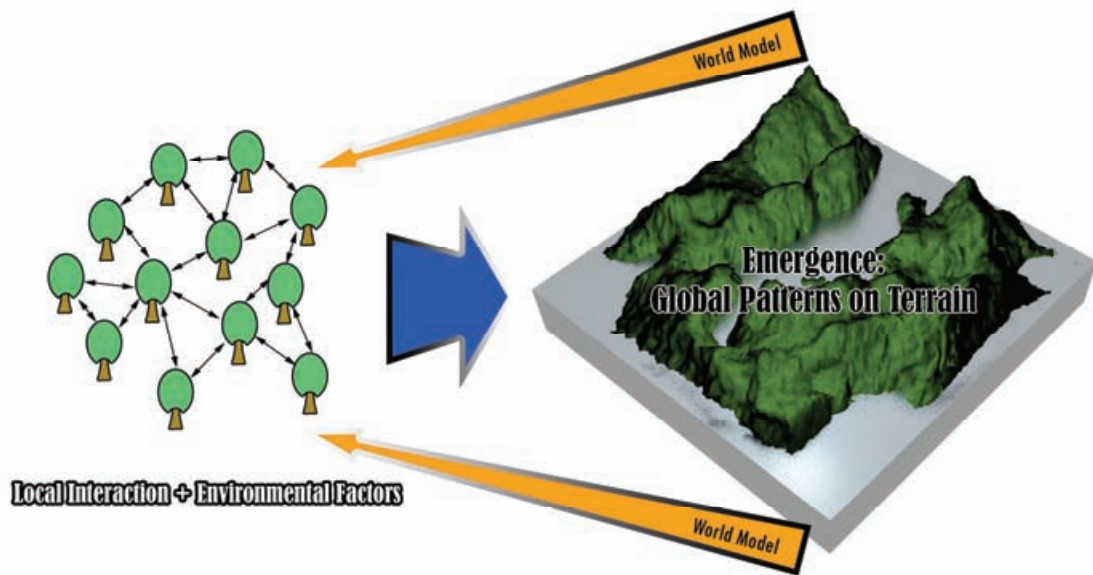


Figure 74. Perception of a landscape as a large organism composed of vegetation as its entities

Many examples from alife research have shown that building alife from knowledge of natural life requires the distillation of their characteristics into simple rules. Since the first Cellular Automata (CA) experiments by John von Neumann [161], which later spawned the two-dimensional version of John Conway's *Game of Life*, the use of quite simple rules to generate complex patterns and behaviours in physical systems have been demonstrated. The simulation of schools of fish [195, 198, 199] is one example where the rules of schooling are a consequence of the tendency of fish to avoid others that are too close. They align their body to those at intermediate distances, and to move towards others that are far away. Model of flocks of birds [194], as mentioned earlier, is another example. Complexity also arises courtesy of such factors as the presence of different species, symbiosis [320], evolution and the inclusion of the environment [202, 321].

How can the rules be modelled from vegetation as a complete entity? Observations and studies of vegetation biology and plant ecology have shown that their life cycle, preferences, and tolerance to environmental benefits and threats can be described by states and rules with structural characteristics similar to those of computer algorithms. Furthermore, a mapping of real world parameters to variables within the program should appropriately synthesise their behaviour, much like studies of other alife-based organisms. In addition, vegetation reaction to environmental factors such as temperature variation, and competition for sunlight, nutrients, space and so on are nothing more than simple rules of preferential tolerance that can be described in a computer

program based on variable states in variable conditions. With a small amount of “fine tuning” of the properties of vegetation, individual plants can be modelled to a level of accuracy sufficient for solving problems in vegetation distribution research.

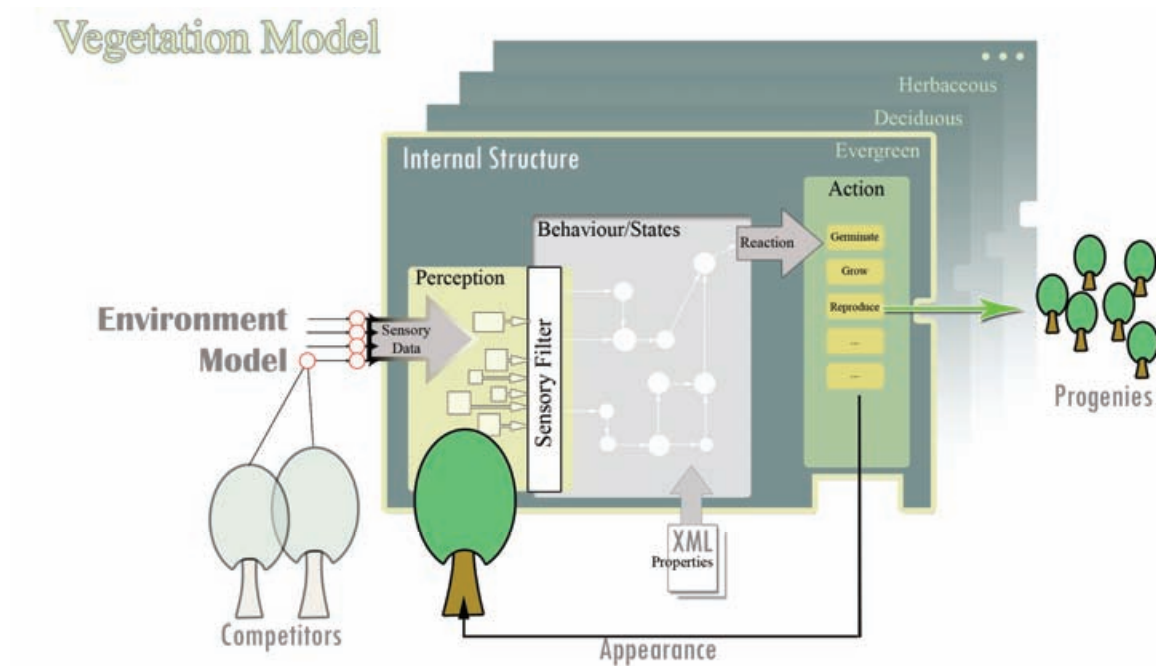


Figure 75. A generic agent-based vegetation model

In Figure 75, a generic model of vegetation used in this research is illustrated. The agent-based plant possesses sensors for sensing ecological and seasonal changes, both reacting and adapting to variations based on properties and preferences, which includes seed germination and adaptability information of plants towards different environmental conditions. The artificial vegetation germinates from a seed before beginning its lifecycle of growth, adaptability, competition, reproduction, and death. The procedure for synthesising vegetation into computational models of life necessitates the generalisation and distillation of their behaviours into rules. These rules are defined in the sub-sections below.

In summary, the vegetation modelling covered in this section is based on the concept of emergence by the synthesis of vegetation using concepts in Artificial Life. This section also address issues that are partial and lacking from a review of literature related to vegetation modelling. The issues are listed below:

- Generic vegetation model – capable of including all vegetation types
- Individual plant life cycle – seed, seedling, young, mature, and old
- Generic plant life cycle – growth, survival, competition, and reproduction
- Vegetation forms (trees, shrubs, herbs, grass, and etc)
- Seasonal differences (evergreen, deciduous)
- Competitions based on vegetation types - canopy, density of leaves, height, and vegetation types
- Competition for space and sunlight
- Nutrient accessibility
- Adaptability to ecological factors and resources – sunlight, temperature, carbon dioxide, altitude, soil, hydrology, and etc)
- Ground conditions – soil acidity, soil depth, soil texture, ground slopes, and etc

4.3.1. High-Level Vegetation Artificial Life

In order to synthesise vegetation, the lifecycle of a plant was reduced to four high-level stages – Seed–Germination–Growth–Reproduction. In the seed¹ state and the first instance of germination, the artificial plant passes through the survival phase where environmental factors act as a destructive force in the attempt to terminate the plant life by having the plant react to ecological signals. The growth and reproduction of the Artificial Life plant is in the phase where competition occurs and is characterised not only by ecological factors, but also the competition of resources such as space, nutrients, and sunlight. This cycle of Artificial Life is common to all species of plants introduced into the system except for the span of time they occupy to complete each cycle as can be observed in annuals, biennials, and perennials. During an artificial plant's reproductive stage, pollination and fertilisation are deemed to have occurred and seeds are dispersed at proximity or at a distance based on plant sizes and the type of dispersal agents used.

Plants are environmentally-sensitive and are modelled as cybernetic systems, sending and receiving information from the environment. Plants at interactive distances communicate information regarding their canopy sizes, height, and form for competition of sunlight, space, and

¹ Seed in the research presented here also refers to candidate offspring as not all plants reproduce through seeds.

nutrients. As such, their well being is directly affected by the environment and vegetation at proximity. Knowledge in the category listed below is necessary for modelling plant life:

- The life cycle of different plants.
- The preferences of plants.
- The growth type of plants (evergreen, deciduous, etc).
- The tolerance or adaptability of different plants to different environmental conditions.
- The reproductive life cycle.
- The conditions suitable for seed germination and growth.

For visualisation, 3D representations of plants are illustrated using 3D models. The models describe the stages of growth with interpolation between the sizes as its age increases (Figure 76).



Figure 76. 3D Representation of artificial vegetation in different stages of growth

4.3.2. Plant Classification

In the research presented here, plant names are specified according to the Binomial system of classification. However for practicality of synthesising vegetation lifecycle, taxonomic categories between the level of genus and kingdom employed by botanists are not used. Instead, plants are grouped according to their lifecycles, visible size and shape of growth. Three examples of taxonomic divisions are *Coniferophyta* (conifers), *Anthophyta* (flowering plant), and *Pterophyta* (ferns). In this research (Figure 77), the *Pinus* would be grouped under evergreen whereas *Corylus Avellana* (Hazel) is grouped under the deciduous category. Ferns are placed under the perennials category as their lifecycle is somewhat similar. The grouping of plants under the evergreen and

deciduous tree type implies that they live from year to year. Annuals are plants that complete their lifecycle in one growing season, Biennials needed two growing seasons to complete its lifecycle (vegetative growth – dormancy/inactive – flower – reproduction – die in second season). Perennials that live for more than three years are categorised as herbaceous. The reason for the separation of tree types from herbaceous plants is for synthesising competition and will be covered in section 4.3.9 and 4.3.10. ‘Grass’ as a sub-level of ‘Vegetation’ may be added as an additional factor for competition. The *Organism* is a top-level abstract class in the object-oriented system available for extension of other living organisms such as animals, birds, fish and insects later in future research. As we are attempting to synthesise vegetation lifecycle, the hierarchy of classes illustrated below is sufficient.

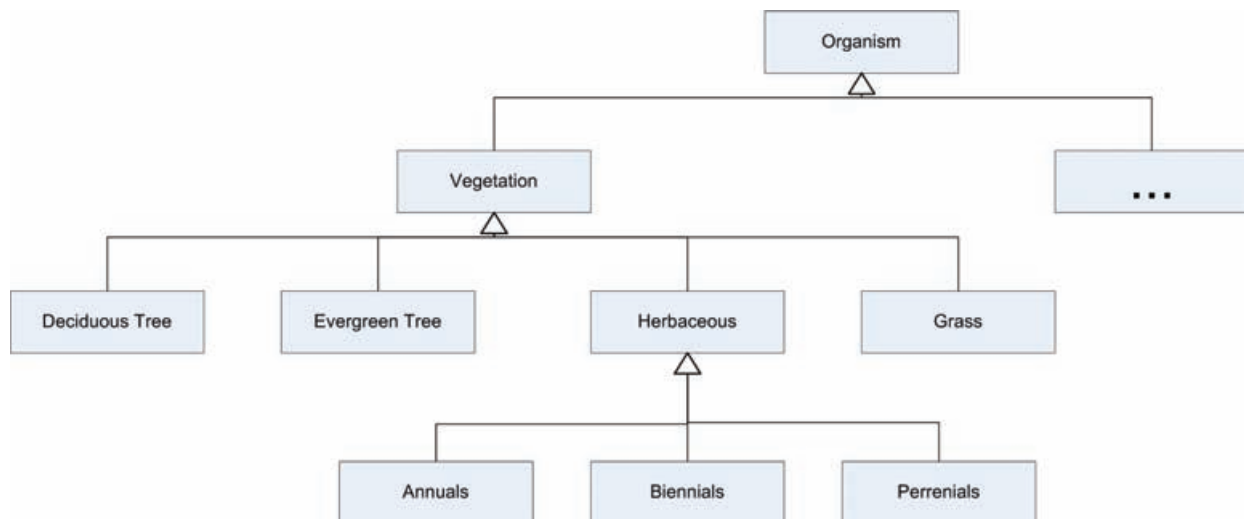


Figure 77. Vegetation hierarchy for synthesis of vegetation growth

4.3.3. Vegetation DNA

DNA of plants are described using XML, containing properties for growth, reproduction, adaptation, and seed germination. Each category of descriptor stores information regarding the plant's maximum age, plant types, adaptation, tolerance to environmental factors, reproductive functions and seed dispersal methods, and the conditions for seed germination. The DNA has potentials for synthesising genetic diversity between similar species in future implementations. An example XML file of the Birch species is shown below.

```

<Plant>
  <Name>
    <Common>Birch</Common>
    <Scientific>Betula papyrifera</Scientific>
  </Name>
  <Info>
    <MeasuringUnit>Metres</MeasuringUnit>
    <Memo>The Birch Tree</Memo>
  </Info>
  <File>
    <MeshDead>BirchDead.X</MeshDead>
    <MeshSeed>BirchSeed.X</MeshSeed>
    <MeshSeedling>BirchSeedling.X</MeshSeedling>
    <MeshYoung>BirchYoung.X</MeshYoung>
    <MeshMature>BirchMature.X</MeshMature>
    <MeshOld>BirchOld.X</MeshOld>
  </File>
  <Growth>
    <MaximumAge>50</MaximumAge>
    <Type LeafType="Deciduous">Tree</Type>
    <BestSoil>Clay</BestSoil>
    <AcceptableSoil>Compost</AcceptableSoil>
    <MaxHeight>30</MaxHeight>
    <Canopy>23</Canopy>
    <LeafDensity>0.7</LeafDensity>
  </Growth>
  <Tolerance hardiness="0.3">
    <Sunlight Upper="0.98" Lower="0.4">0.5</Sunlight>
    <Temperature Upper="36" Lower="-6">20</Temperature>
    <Moisture Upper="0.6" Lower="0.35">0.5</Moisture>
    <Nutrient Upper="0.7" Lower="0.2">0.55</Nutrient>
    <Elevation Upper="760" Lower="-5">312</Elevation>
    <Space Upper="0.45" Lower="0.01">0.25</Space>
    <CO2 Upper="0.6" Lower="0.4">0.5</CO2>
    <SoilPh Upper="8" Lower="1.5">4</SoilPh>
    <SoilDepth Upper="1" Lower="0.2">0.4</SoilDepth>
    <Ground Upper="0.5" Lower="0">0.3</Ground>
  </Tolerance>
  <Reproduction>
    <Type>Sexual</Type>
    <DispersalType>Discharge</DispersalType>
    <SexualMaturityAge>8</SexualMaturityAge>
    <SeedCount>60</SeedCount>
    <AverageGerminationPercentage>20</AverageGerminationPercentage>
    <PollenReleaseDateStart>July</PollenReleaseDateStart>
    <PollenReleaseDateEnd>August</PollenReleaseDateEnd>
    <SeedingMonth>September</SeedingMonth>
  </Reproduction>
  <Germination>
    <DaysStart>30</DaysStart>
    <DaysEnd>180</DaysEnd>
    <MonthStart>March</MonthStart>
    <MonthEnd>August</MonthEnd>
    <Season>Autumn</Season>
    <TemperatureLower>15</TemperatureLower>
    <TemperatureUpper>28</TemperatureUpper>
    <MoistureLower>0.32</MoistureLower>
    <MoistureUpper>0.58</MoistureUpper>
    <Soil>Clay</Soil>
  </Germination>
  <KnownDisease />
</Plant>

```

4.3.4. Vegetation Preference

Different species of vegetation possesses different preferences towards the environment. Preferences can also be defined as tolerance or adaptability. These preferences are defined within the virtual plant's DNA. Preferences that are well defined in botany is described with standard values whereas those which are not are measured between $[0,1]$. For example, temperature preferences of each species of plants are well defined. Tolerance to sunlight however, is often vague, with descriptions such as “full sun”, “partial shade”, “shady areas”, and etc. Hydrological preferences are similarly, often described with a relative comparison between the ecology of interspecies preferences from studies of population concentrations. Grime, Hodgson and Hunt's *Comparative Plant Ecology* [17] is one example. In the alife framework, these plant tolerances use a relative measure. Figure 78 illustrates an example approach used in the research presented here for modelling hydrological preferences.

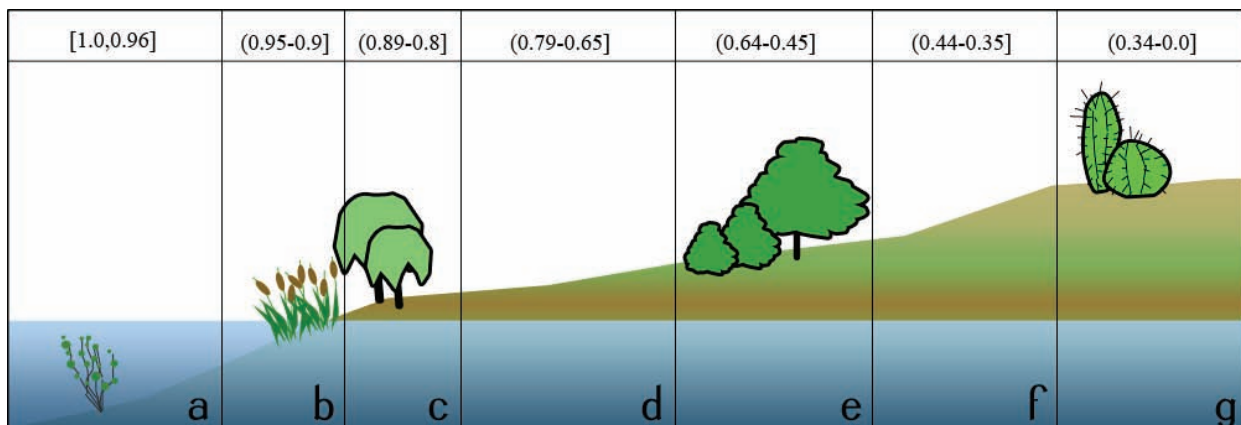


Figure 78. An example of how vegetation preferences are modelled. The illustration showed plant adaptability towards hydrology and soil moisture content.

In band *a*, the tolerance of aquatic plants is between 1.0 and 0.96~. Band *b* and *c* shows the tolerance of plants that lived near water sources. These are Cattails, Papyrus, Willows, and etc. Band *d*, *e*, and *f* are land based plants with plants in band *e* having a moderate preference. Plants preferring dry conditions can be seen in band *g*.

4.3.5. Plant Growth Cycle

The growth of a plant is proportional to its age given that the conditions are favourable in the VE, although environmental factors and competition for resources from other plants may retard its size. The growth mechanism persists according to senescence, after which a plant expires. The age of the plant is incremented only after the seed is germinated.

At each time step the plant goes through the cycle,

Listing 6:

```
1. IF in seed stage
2.   Germination Test
3. ELSE
4.   IF age is over maximum age OR fitness has depleted
5.     Plant dies and decays, adding nutrients to the ground
6.     Remove plant when decay is complete
7.   ELSE
8.     Increment age
9.     Change appearance based on age
10.    Compute fitness by
11.      Sensing ecological signals
12.      Competing with plants at proximity
13.    Check season for Reproduction
```

4.3.6. Plant Reproduction

There are two types of reproduction in plants, sexual and asexual. In contrast to sexual reproduction, asexual reproduction requires no meiosis and the merging of gametes from two parents of the same species, but instead reproduces quickly via stems, leafs, or roots. Even though the alife framework allows asexual reproduction, the plant entities are cloned in the work presented here.

The initiation of reproduction in plants occur when environmental signals and seasonal changes take place (e.g. spring in contrast to winter). Depending on the variation of reproduction in plants, at the appropriate time pollination and fertilisation are deemed to have occurred and seeds are dispersed onto the landscape. The relevant algorithm is shown below,

Listing 7:

1. *IF season is right*
2. *IF environmental conditions matches plant reproduction condition*
3. *IF vegetation is a tree or shrub*
4. *Disperse seed onto landscape using the Growth-Seed ratio*
5. *Else for other type of vegetation*
6. *Disperse seed onto landscape using the fitness-seed ratio*

Based on the size of the plant, the majority of seeds are dispersed in a radial fashion within a dispersal distance around the parent plant. Dispersal agents [322] such as ants, and vertebrates are simulated by dispersing a user-specified percentage of the seeds across the landscape:

Listing 8:

1. *FOR all seeds on the plant*
2. *Get dispersal distance of each seed based on plant size*
3. *Disperse a percentage of seeds anywhere on the landscape*
4. *Disperse other seeds around the plant within the disperse distance*

Two different methods are used for determining the number of seeds in Listing 7.4-7.6. The number of seeds that are produced by tree or shrubs are dependent on its age of sexual maturity and the maximum age. This means that the more the plant grows, the more seeds are produced. For all other types of vegetation, mostly herbaceous plants, the number of seeds are based on the fitness-seed ratio. The fitness-seed ratio is,

$$s_{herb} = s_{max} f$$

Where the total number of seeds produced is s_{herb} , s_{max} is the maximum number of seeds the plant is able to produce, and f is the fitness of the plant calculated using the fitness function presented later (4.3.12).

The growth-seed ratio is modelled using the equation below.

$$s_{tree} = \left(1 + e^{\frac{m}{2} - a \frac{x}{m}} \right)^{-1}$$

Where s_{tree} is the total number of seeds produced for tree or shrub types, a is the current age, m is the maximum age, and x is the age of sexual maturity. The behaviour of the equation is shown in Figure 79.

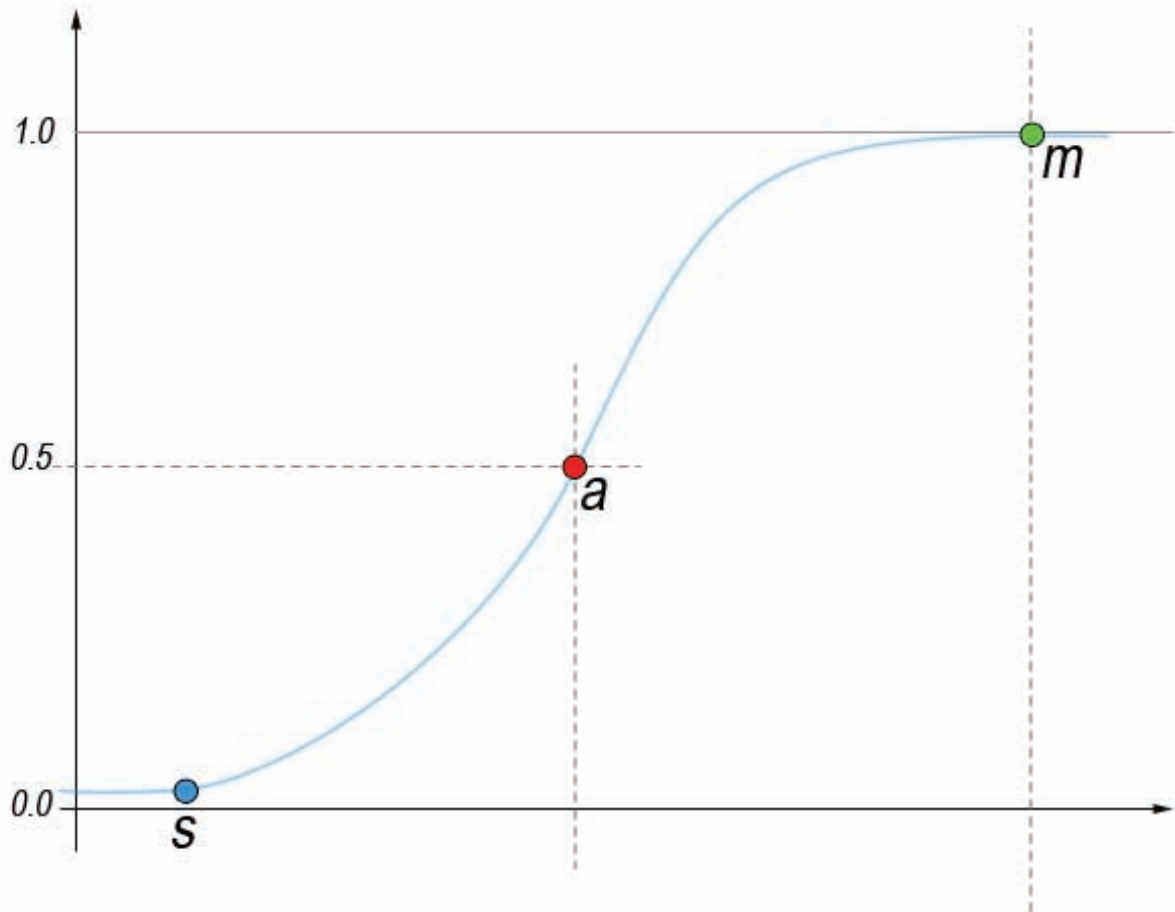


Figure 79. Concept – Behaviour of growth-seed ratio for determining the number of seeds produced

4.3.7. Seed Germination

The seeds of most plants require a period of dormancy before germination. In certain plants, dormancy usually cannot be broken except by exposure to cold or to light via a chemical inhibitor. In our study, seeds are assigned a seed age measured in days where the dormancy period is tested. The *DaysStart* and *DaysEnd* assigned to the seed (as described in the plant DNA) is a probable period where the germination will occur before which the chemical inhibitor is broken down. The

ending of the dormancy at any time within the period is simulated with a rate of 0.2 probability of occurrence. The ideal condition for seed germination such as the dormancy period, seasons and month, temperature preferences, moisture and soil types for this study can be obtained from Thompson & Morgan [323]. The algorithm below describes the germination process.

Listing 9:

```

1. IF seed is within the dormancy period
2.   Increment seed age
3. ELSE IF seed age is between DaysStart and DaysEnd
4.   IF Dormancy is over
5.     IF environmental conditions:  $L < E < U$ 
6.       Seed is germinated
7. ELSE IF seed is past DaysEnd
8.   Remove seed as dead

```

In listing 9.5, the seed germination preference uses the environmental germination rule where E is the current environmental condition, and L and U are the ideal range of condition for seed germination.

4.3.8. Plant Adaptability

Adaptation in vegetation denotes avoidance and tolerance to environmental hazards [315]. For example, four main kinds of adaptation to fire are:

1. Resistance where plants have thick, fire-proof bark,
2. Regeneration by sprouting from root stocks or surviving stems,
3. Possession of specialised underground organs like the lignotubers of certain Eucalyptus species,
4. Specialised, long-lived fruits which accumulate on the plant over a number of years, only opening to release their seeds after the passage of a fire.

Drought tolerant plants adapt by improving their water relations both by increasing their efficiency in extracting and storing water, and by reducing the rate at which they lose water through *evapotranspiration* [324]. Many plant species are killed by even the briefest exposure to water-logging. Herbaceous vascular plants from permanently wet sites show a range of morphological and physiological traits including:

1. Anatomical features allowing oxygen transportation to the roots,
2. The ability to exclude or tolerate soil toxins, and
3. Biochemical features which allow prolonged fermentation in the roots [325].

Other species, like *Populus deltoids*, can even germinate underwater and their seedlings can survive considerable periods of submersion [326]. Plants living in permanent shade include Ferns, mosses and lichens, as well as vascular plants of the undergrowth in evergreen forests. These species must maximise their photosynthesis gain from the low levels of energy they receive, by means of reduced respiration rate, increased unit leaf rate, increased chlorophyll per unit leaf weight, increased leaf area per unit weight invested in shoot biomass [327, 328]. Plants that adapt to low nutrient availability are generally small in size and have a tendency to have small, leathery, long-lived leaves, and a high *root : shoot* ratios [329, 330]. Other physiological traits include slow growth rates, efficient nutrient utilisation, efficient mechanisms of internal nutrient recycling to ensure minimal losses through leaf fall, exudation or leaching [331]. Plants found to adapt to extremes of cold temperatures often possesses small, long-lived leaves. Carbohydrate storage organs allow them to grow rapidly in the spring and also to accumulate resources over several brief growing seasons before investing in a burst of seed production. In extremes of hot temperatures, plants show small, dissected leaves which increase the rate of convective heat loss and physiological tolerance of very high tissue temperatures [315]. Adaptations of plants in these studies showed that extreme environmental conditions may be countered by developing traits tolerant of surviving in hazardous settings. As plants in the Mesolithic setting have already developed adaptable traits prior to this period, an abstract adaptation concept is used in the research presented here.

The preferences of plants vary across different species. It is known that certain plants are more tolerant to certain environmental condition than others. In the VE, each alife entity possesses sensors to sense the environment and has the ability to react to each environmental factor according to its preferences specified in its DNA. The formula below is an equation within each plant that can be applied to measure each environmental condition. Favourable conditions that suit the plant's preference will maintain its fitness whereas harsh conditions may decrease it collectively over time to the eventual termination of the plant life.

Based on the assumptions above, an adaptability function is developed. The equation A_i computes the upper and lower tolerance based on the preferred range:

$$A_i = \begin{cases} 1 & \text{if } p_i - b|p_i - L_i| \leq C \leq p_i + b|p_i - U_i| \\ -\frac{1}{|U_i - p_i + b|p_i - U_i|} |C - p_i + b|p_i - U_i| + 1 & \text{if } p_i + b|p_i - U_i| < C \leq U_i \\ -\frac{1}{|L_i - p_i - b|p_i - L_i|} |C - p_i - b|p_i - L_i| + 1 & \text{if } L_i \leq C < p_i - b|p_i - L_i| \\ 0 & \text{otherwise} \end{cases}$$

where C is the current environmental condition as a signal from projected temperatures, sunlight, moisture, and elevation from the VE, U_i and L_i are respectively the upper and lower tolerance; p_i is the ideal condition for the plant; and b is the hardiness of the plant for defining the range extending the ideal condition to its upper and lower tolerance. Two other functions are derived from the equation above. The first measures only the upper bound tolerance so that any values below the ideal range will yield a full fitness level (1.0). This is useful for situations where the lower bound is not needed. For example, most plants can tolerate open spaces, that is, a plot of land where there is no competition for space from other plants. In this case, the upper bound may represent the amount of space occupied by other plants and are measured. Spaces proceeding below the extended ideal range tolerated by the plant however, are considered as open spaces, which yields a full fitness level for the plant. The second is the exact reverse of the first measuring only the lower bound and yielding a full fitness for values proceeding beyond the extended ideal range. For example, the second equation can be used for measuring soil depth [0,1] where the earth has no depth/shallow (0.0), medium depth (0.5), to infinitely deep soils (1.0). The upper bound equation is defined below,

$$A_i^{Upper} = \begin{cases} 1 & \text{if } 0 \geq C \leq p_i + b|p_i - U_i| \\ -\frac{1}{|U_i - p_i + b|p_i - U_i|} |C - p_i + b|p_i - U_i| + 1 & \text{if } p_i + b|p_i - U_i| < C \leq U_i \\ 0 & \text{otherwise} \end{cases}$$

The lower bound equation is defined below.

$$A_i^{Lower} = \begin{cases} 1 & \text{if } p_i - b|p_i - L_i| \leq C \leq 1 \\ -\frac{1}{L_i - p_i - b|p_i - L_i|} |C - p_i - b|p_i - L_i|| + 1 & \text{if } L_i \leq C < p_i - b|p_i - L_i| \\ 0 & \text{otherwise} \end{cases}$$

Figure 80 are graphical representations of the equations and Figure 81 depicts the function used for measuring various ecological factors in relation to the tolerance of a plant.

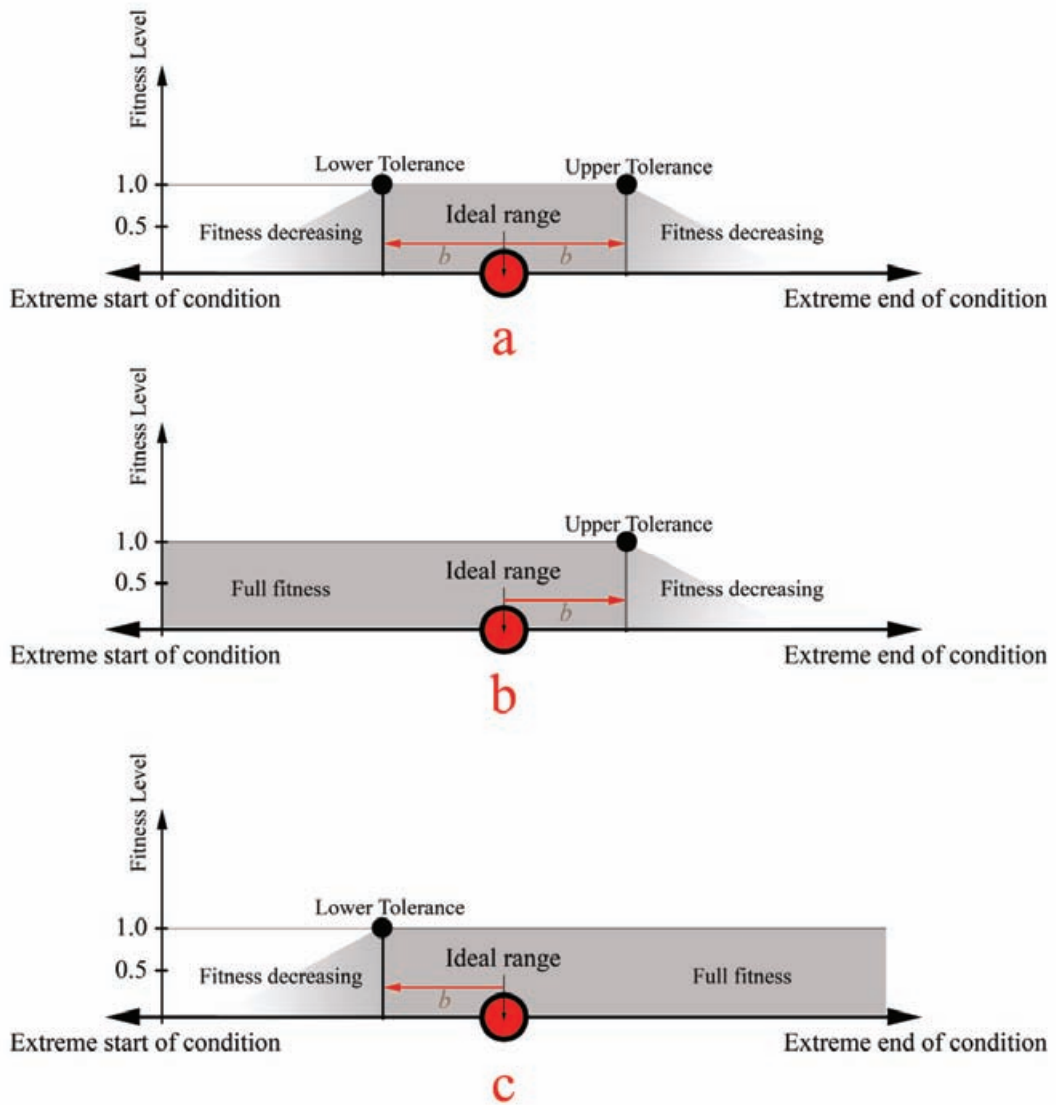


Figure 80. A graphical representation of the adaptability function (a) and the upper (b) and lower (c) bound functions derived from it

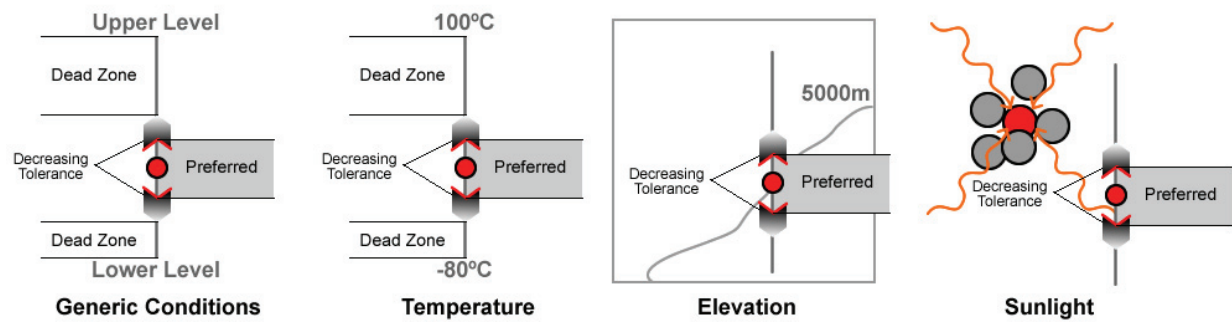


Figure 81. The adaptability function applied for measuring various ecological factors

4.3.9. Competition for Space

Competition for space amongst plants is dependent on the size and form of the plant (tree, bushes, and undergrowth) and their distances between each other. The rule is defined as follows: a plant is advantageous if its establishment in age and its largeness in size are greater than its adjacent plants. The adaptation rules of a plant also differentiate trees from shrubs and herbs in that the latter will be more tolerable to crowded situations. Figure 82 demonstrates the logic for competition in three different scenarios. Figure 82a is a shrub type group inclusive of herbaceous plants, *b* are tree types and *c* are hybrid groupings of shrubs and trees. In *a*, shrub 1 is taller and therefore has no competitor; the use of space for shrub 2 is competed by shrub 1, 4, and 5; shrubs 4 and 5 compete for space with one another and with shrub 3. In *b*, tree 1 being larger, has no competitor. Tree 2's usage of space is competed by tree 1. Trees 3, 4, and 5 compete for space. In a hybrid setting in *c*, tree 1, 6, 7 and shrub 5 competes; shrub 4 competes with both 3 and 5. There are no competition between shrubs 2, 3, 4 with tree 1.

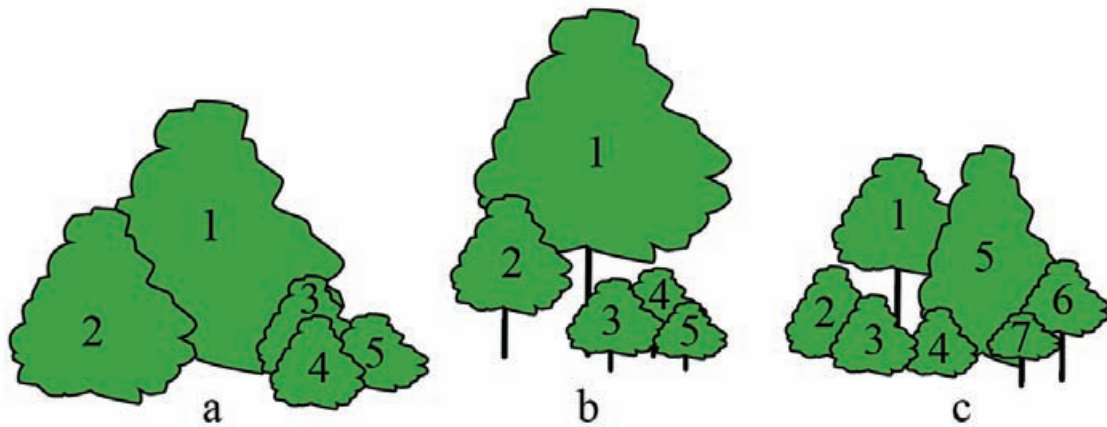


Figure 82. Competition for space

The logic in Figure 82 can be reduced to the simple rules. There is competition only if the opponent is larger and is a bush type or if it is equal or smaller in size with different intensity of the use of space for larger and smaller competitors:

Listing 10:

```

1. FOR every plant of which canopy overlaps source plant
2.   IF the competing plant is larger and is a bush
3.     Compute larger opponent's use of space
4.   ELSE
5.     Compute smaller opponent's use of space
6.   Add to value of the space occupied
7. NEXT
8. Compute use of space with generic adaptability function

```

The opponent's use of space is dependent on its size. The intensity of the competition between different agent and competitor sizes are modelled. Two formulas were used for determining the occupation of space for larger opponent, or opponent smaller or equal in size. Figure 83 illustrates the concept where the green curve represents the space being occupied by a plant smaller or equal in size to the agent plant (red dot) and the blue curve represents the space occupied by a larger plant. The point (red) where the green and blue curves meet is the size of the source plant which determines where the green curve ends and where the blue curve begins. This means that when the source plant is at the size shown, the space occupied by a plant of the same size (end of green curve) is 0.25. The blue curve shows that the larger the opponent, the more space is occupied.

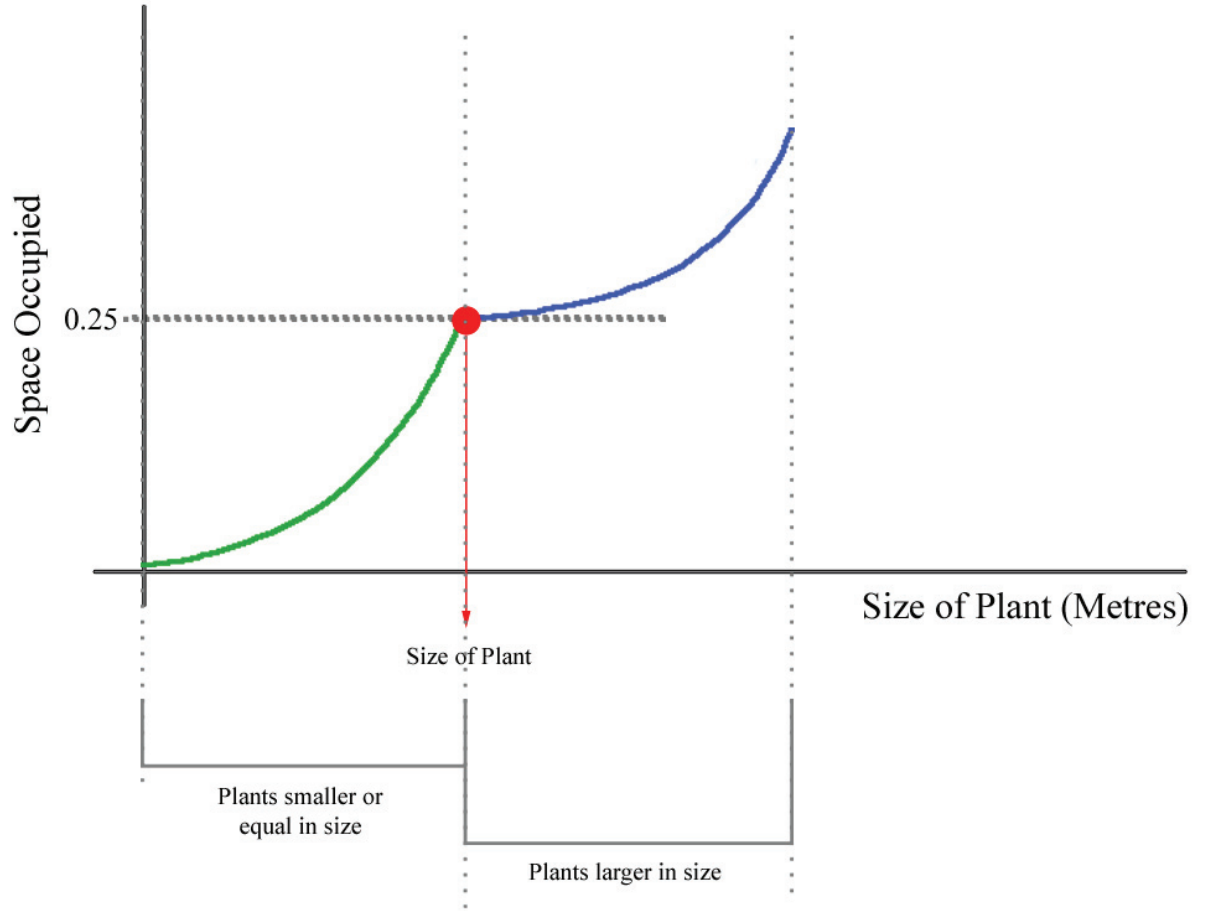


Figure 83. Concept – Intensity of competition between opponent larger and opponent smaller or equal in size

In listing 10.3, the space S_i occupied by larger opponents is defined with,

$$S_i = L \left[e^{\frac{x_i - ws}{I}} + 1 \right]$$

where $L=[0.25,0.3]$ is the space used if the source plant is at size s , x_i is the size of the opponent. For size $s \leq 10$ metres, $I=5$, $w=3$. For size $10 > s < 25$ metres, $I=5$, $w=2$. For size $s > 25$ metres, $I=10$, $w=2$.

In listing 10.5, the space S_i occupied by smaller opponents is defined with,

$$S_i = L e^{\frac{x_i - s}{I}}$$

where $L=[0.25,0.3]$ is the intensity of the use of space, x_i is size of the opponent, s is the size of the source plant. For size $s \leq 10$ metres, $I=1$. For size $10 > s < 25$ metres, $I=5$. For size $s < 25$ metres, $I=10$.

For Listing 10.6, the space occupied by all opponents is,

$$C = \begin{cases} 1 & \text{if } \sum_{i=1}^n S_i > 1 \\ \sum_{i=1}^n S_i & \text{if } 0 \leq \sum_{i=1}^n S_i \leq 1 \\ 0 & \text{otherwise} \end{cases}$$

Where C is the totality of the space occupied by opponent plants, n is the number of plants in competition, i is an opponent, and S_i is the space occupied by the opponent.

4.3.10. Competition for Sunlight and Shade Temperature

The amount of light that may be received by a plant is determined by its height in relation to others. In larger plants, the density and radius of the canopy determines the covering (shade) toward smaller plants or the undergrowth. It is possible that the totality of canopies completely covers sunlight from reaching the undergrowth.

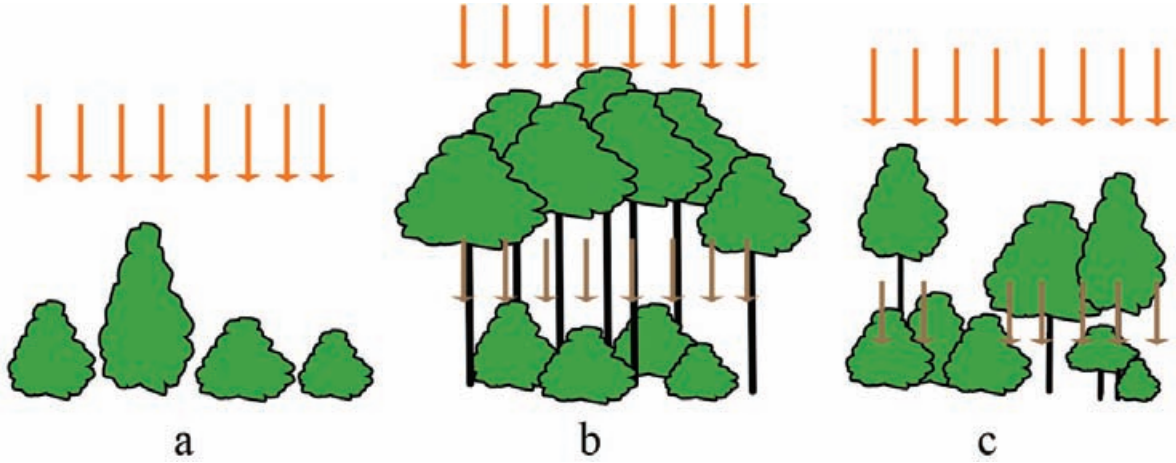


Figure 84. Effective sunlight and shade

Figure 84 is an illustration of the competition for effective sunlight in a local setting. The plants in group *a* grows in a sparse setting and the effective sunlight is not annulled by any shade, therefore, no competition occurs. In group *b*, the brush growing under large trees in a forest setting receives limited sunlight due to the shades from the trees. In a dense forest, there is a possibility that the canopy of trees completely filters the sunlight from the undergrowth. Group *c* shows a collection of plants that are not fully covered, receiving low sunlight through the canopy of trees.

The above scenarios can be generalised as rules for computation of effective sunlight,

Listing 11:

1. FOR every plant of which radius of canopy overlaps source plant
2. FOR every plant that is taller by one and half times
3. Collect effective shade from opponent plant
4. NEXT
5. NEXT
6. Compute effective sunlight received by source plant

In listing 11.3, the effective shade cast by an opponent U_i is,

$$U_i = c_i^{-1} \left[d_i \left| \sqrt{(x_i - x_s)^2 + (y_i - y_s)^2} - (r_i + r_s) \right| \right]$$

Where i is the individual opponent with location, x_i and y_i , canopy c_i , and leaf density d_i . The location of the source plant is at x_s , y_s with radius r_s . Figure 85 illustrates the concept of

competition between two plants where the overlap value (red line) is used together with the canopy and density of the plant to determine the effective shade produced by the opponent plant.

The effective shade collectively of all opponents H is,

$$H = \begin{cases} 1 & \text{if } \sum_{i=1}^n U_i > 1 \\ \sum_{i=1}^n U_i & \text{if } 0 \leq \sum_{i=1}^n U_i \leq 1 \\ 0 & \text{otherwise} \end{cases}$$

Where n is the number of plants in competition, i is an opponent. The effective sunlight S received by a plant under the shade of larger plants in listing 11.6 is,

$$S = L(1 - H)$$

Where $L=[0,1]$ is the global sunlight before deducting from the effective shade H .

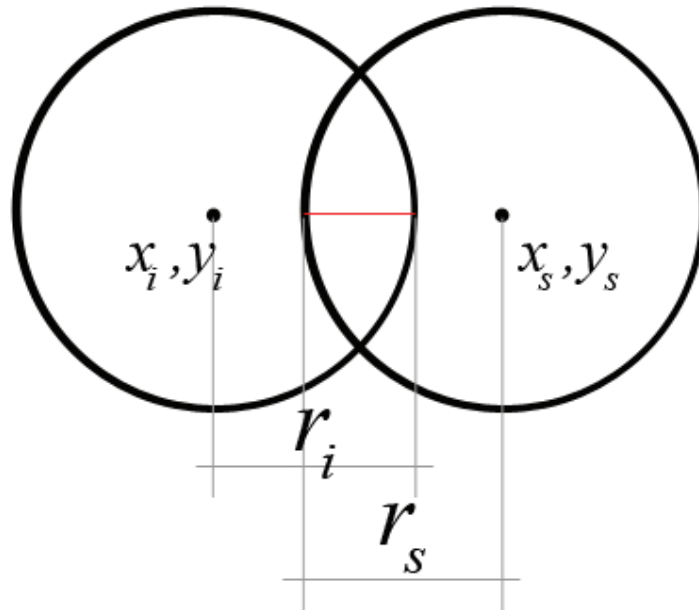


Figure 85. Concept – Overlapping plants for sunlight competition

In shaded areas under large clusters of trees, the temperature may decrease slightly. This local temperature variation is simulated using the effective shade as defined below,

$$T_{shade} = H(-T_{max})$$

Where H is the effective shade collectively cast by opponent plants, T_{max} is the maximum decrease in temperature, and T_{shade} is the total decrease in temperature that should be added to the effective temperature T_{eff} defined in section 4.4.1.

4.3.11. Nutrient Accessibility and Plant Decay

Nutrients exist in the soil and the decay of organic matter adds to the level of nutrients accessible to nearby plants. This means that within the vicinity of clusters of vegetation, the decaying organic matter such as the fallen leaves and plant components generate a higher concentration of nutrients. These nutrients are accessed by plants surrounding the clusters. The availability of nutrients therefore is accessed from three sources – the condition of the soil, decaying components from living agents, and the decaying components from dead agents. The first is a global parameter which varies according to seasonal changes and the latter two supplements the level of nutrients accessible to the local clustering of vegetation communities. Intensity of nutrients naturally increases around a higher number of vegetation clusters and from dead agents. Figure 86 illustrates the availability of nutrients in vegetation clusters. White intensity shows a higher concentration of nutrients. The intensity increases around larger clusters. The global nutrient intensity (at dark grey background value) is variable between seasons (see section 4.4.1).

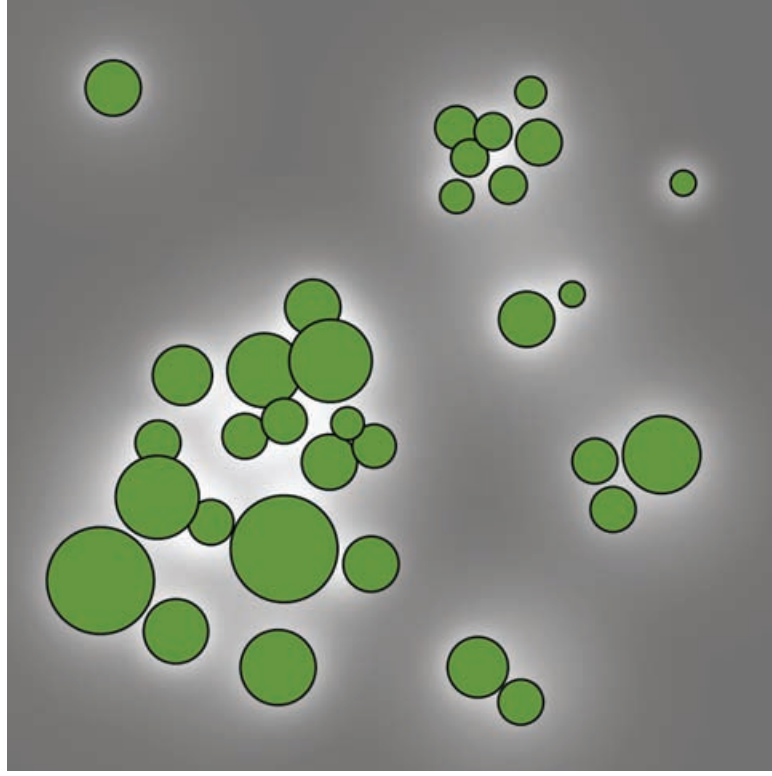


Figure 86. Availability of nutrients near vegetation shown as higher intensity

Listing 12:

1. For every plant at proximity
2. Add to the accessible nutrients based on the canopy and leaf density
3. Next

In listing 12.1, the nutrients produced by an individual plant is accessed only if $\sqrt{(x_i - x)^2 + (y_i - y)^2} - (r_i + r) \leq 2r$, where i is the plant at proximity with location, x_i and y_i . The location of the source plant is at x , y with radius r .

In listing 12.2, the level of nutrients from the decaying components of a living agent nearby is N_i^{living} ,

$$N_i^{living} = c_i^{-1} (2d_i r_i)$$

Where c_i is the canopy of individual agent with leaf density d_i and radius r_i .

After a plant dies, decay of plant matter begins and the plant continues to contribute to the local nutrient until the decay is completed. If a nearby agent has expired and is decaying, the nutrient generated by that plant is N_i^{decay} ,

$$N_i^{decay} = 1^{-1} \left[e^{g(-s_i+td)} \right]$$

Where g is the gradient generally $[0.1, 0.5]$, s_i is the size of the agent at the time of death. t is the time-step from the virtual environment, and d is the rate of decay. The size of the virtual representation is set to decrease over time at the same rate of decay and affects competition for space. Figure 87 shows the rate of decay with different values of s , g and d .

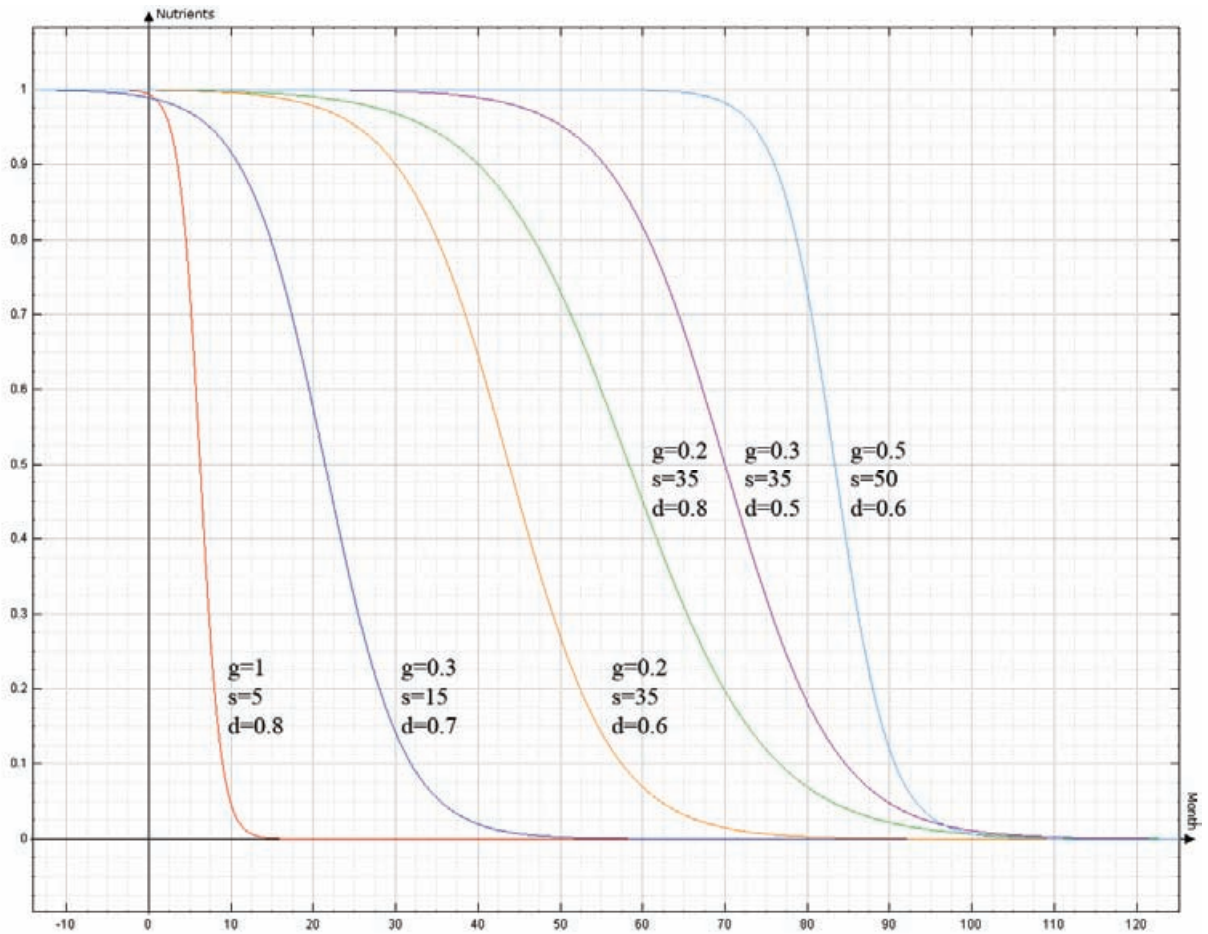


Figure 87. Rate of decay with different gradients, decay, and the size of plant at time of death

The equation below is the effective nutrients received by the source agent,

$$N^{eff} = \begin{cases} 1 & \text{if } N^{global} + \sum_{i=1}^n N_i^{living} + N_i^{decay} > 1 \\ N^{global} + \sum_{i=1}^n N_i^{living} + N_i^{decay} & \text{if } 0 \leq N^{global} + \sum_{i=1}^n N_i^{living} + N_i^{decay} \leq 1 \\ 0 & \text{otherwise} \end{cases}$$

Where n is the number of living and decaying agents at proximity. i , an individual agent, can be either dead N_i^{decay} , or living, N_i^{living} . N^{global} refers to the global nutrient level, which is set to approximate the inverse of the level of sunlight in Figure 89.

4.3.12. Fitness Function

The fitness function discussed in the Artificial Life software framework (4.1.4, Figure 45) determines the fitness of the plant based on their adaptability towards the niches of its biotic and abiotic environment measured through the adaptability function (4.3.8). It is known that within an ecosystem, tiny changes in any of the factors can trigger what scientists in chaos theory dubbed the *butterfly effect* – small changes in initial condition produces large variations in the long term behaviour of the entire ecosystem. This effect is observed in the alife environment developed in this research and it is the measurable fitness function that determines the immeasurable nonlinear outcome of the global emergent behaviour of the ecosystem. Throughout the research, many fitness functions have been experimented with and fine-tuned so that a more accurate version that reflects the real world can be realised. The fitness function defined below operates and controls the sensitivity of individual plant species towards the environment.

$$f_i = C_i M_i S_i T_i g_i^{pH} g_i^{depth} g_i^{cond} [E_i w_1 + N_i w_2 + O_i w_3]$$

Where f_i is the fitness function for a species where $f_i \in [0,1]$ is the result of the measure of adaptability function which measures each factor: C_i is the tolerance based on competition for

space, M_i is based on the soil moisture content, S_i for sunlight, and T_i for temperature. g_i^{pH} is based on the soil pH level, g_i^{depth} for soil depth, and g_i^{cond} for ground condition. Factors considered more crucial of which plants are more sensitive to are listed before the brackets. Factors considered non-threatening are weighted. w_1 to w_3 are weights for controlling the sensitivity of each plant towards the factor where $\sum_1^n w_n = 1$, $n = 3$. E_i is the tolerance based on the location of a plant at its altitude, N_i for nutrient, and O_i is based on the levels of carbon dioxide in the atmosphere.

4.4. Models of Synthetic Environment

Synthesising dispersal patterns of vegetation requires knowing the environment in the target landscape in order to provide equal opportunities for plants suited to different habitat to thrive and compete in:

- The global environment conditions of the landscape – variable seasonal sunlight, temperature, moisture, nutrients, carbon dioxide, hydrology, and temperature-altitudinal ratio.
- The local environment conditions affected by plants at proximity – effective sunlight, shade temperature, moisture, and availability of space, nutrient, soil pH., soil depth, and soil texture or slope conditions.

In the synthetic environment, the terrain is continuous and defined by 3D polygons. Experimental scenarios for studying the behaviours of agent based vegetation uses custom terrains for better control of the environment. The test bed for collective environmental effects on communities of vegetation (Chapter 5) uses reconstructed 3D landscapes derived from the seismic datasets of the Shotton river valley. Climatic settings for the study is derived from various authorities on the subject [262, 263, 270, 273].

4.4.1. Global Environment

The Boreal period, a climatic subdivision of the Holocene epoch, following the Pre-Boreal climatic interval were warm and dry. Radiocarbon dating showed that the period begins at about 9,500bp and ends around 7,500bp. During this period summer temperatures were higher than today by about 2-2.5° C. Temperature also decreases according to altitudinal limits, with a 0.6°C fall in temperature for each 100m above sea level in the Mesolithic.

Global bioclimatic parameters are derived from a monthly mean temperature, sunlight, soil humidity, hydrology, and CO₂ with minor variations using the algorithms in 4.2.1. These ecological signals are sensed by the alife plant for tolerance computation using the adaptability equation. When dealing with large timescales (hundreds to thousands of years), the use of month-time is popular in many systems (e.g. [25, 332, 333]. Figure 88 to Figure 91 shows four global ecological parameters. Except for temperature which reflects real world values, and elevation which depended on the coordinates of the plants, sunlight, moisture and other factors are measured with values in the range $[0,1]$ with full sun and water logging/flooding at 1.0.

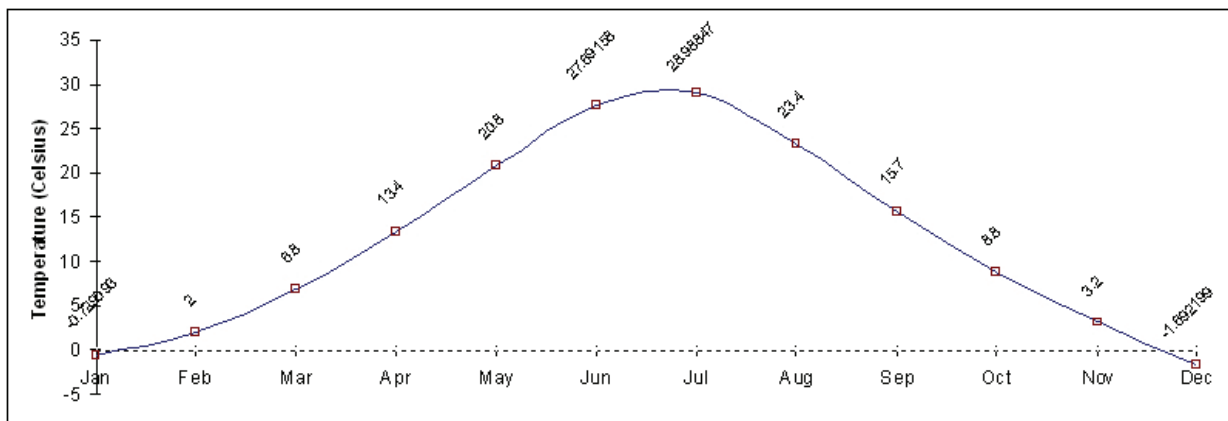


Figure 88. Monthly mean temperature

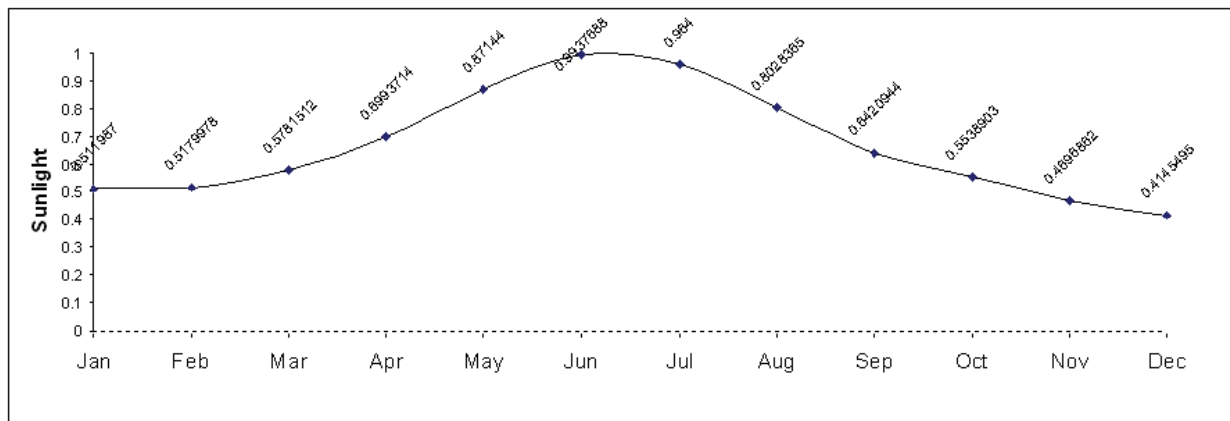


Figure 89. Monthly mean sunlight

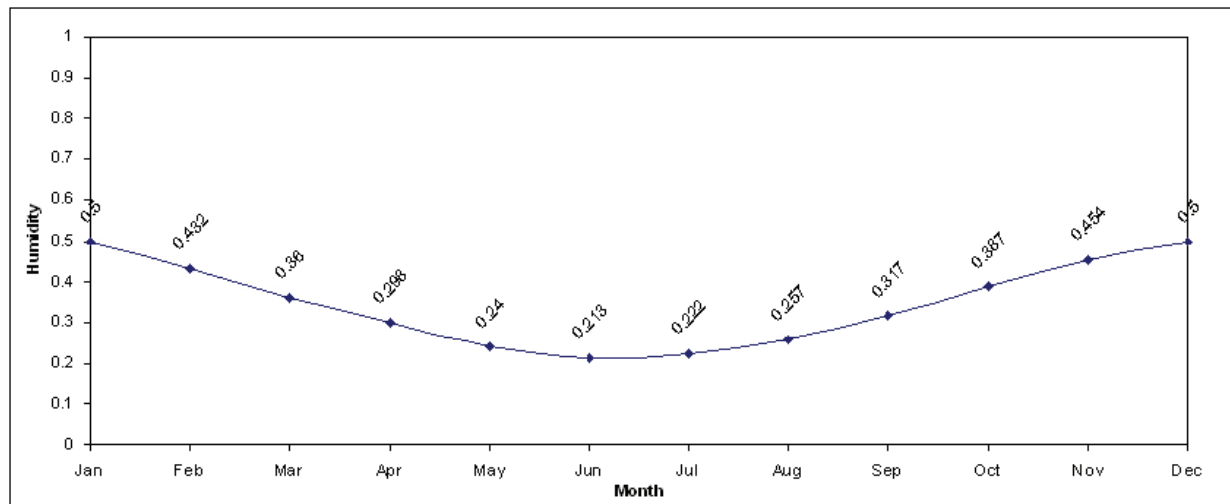


Figure 90. Monthly mean humidity

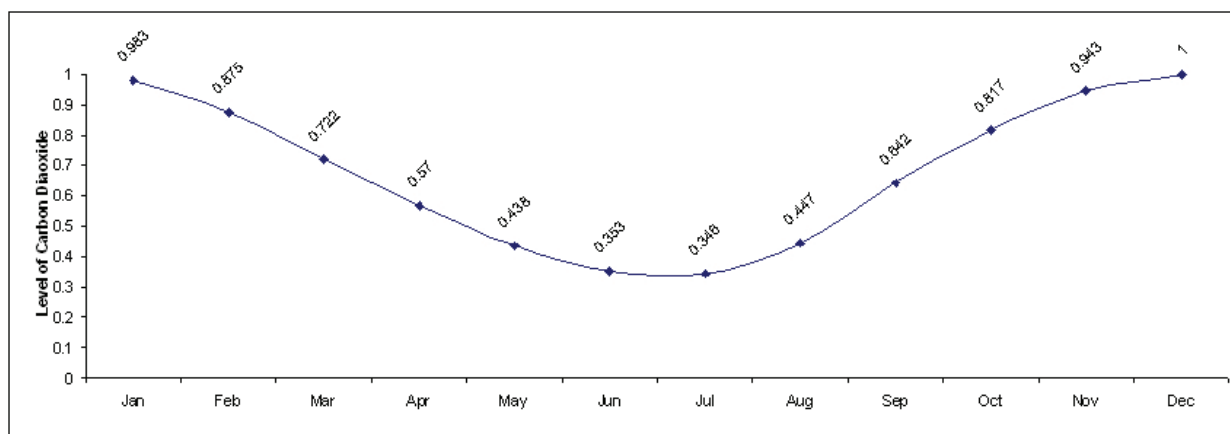


Figure 91. Monthly mean CO2

During the British prehistory, temperature decreases proportionally at 0.6°C per 100m [273], the temperature-altitudinal ratio is simulated with,

$$T_{eff} = \frac{-0.6E}{100} + T_{global}$$

Where T_{eff} is the effective temperature, E is the current altitude where a plant is at, and T_{global} is the seasonal global temperature defined in Figure 88.

Hydrology is measured in the range $[0,1]$. The distribution and increase of water is a continuous gradient to below the water surface so that water plants and plants tolerant to water-logging can be synthesise, the equation for hydrology is defined with,

$$W_{eff} = L \frac{1}{e^{(E-W_{surface})g^{-1}}}$$

Where W_{eff} is the effective moisture level, L is the moisture level below the water surface ($L=0.5$ in Figure 92), E is the current altitude where a plant is at, $W_{surface}$ is the water surface, g is the gradient.

Figure 92 shows a graph with $W_{surface}$ at the default 0m, and rose to 200m. The graph defines the hydrological condition of the soil if the water level is at 0m and 200m within the Virtual Environment.

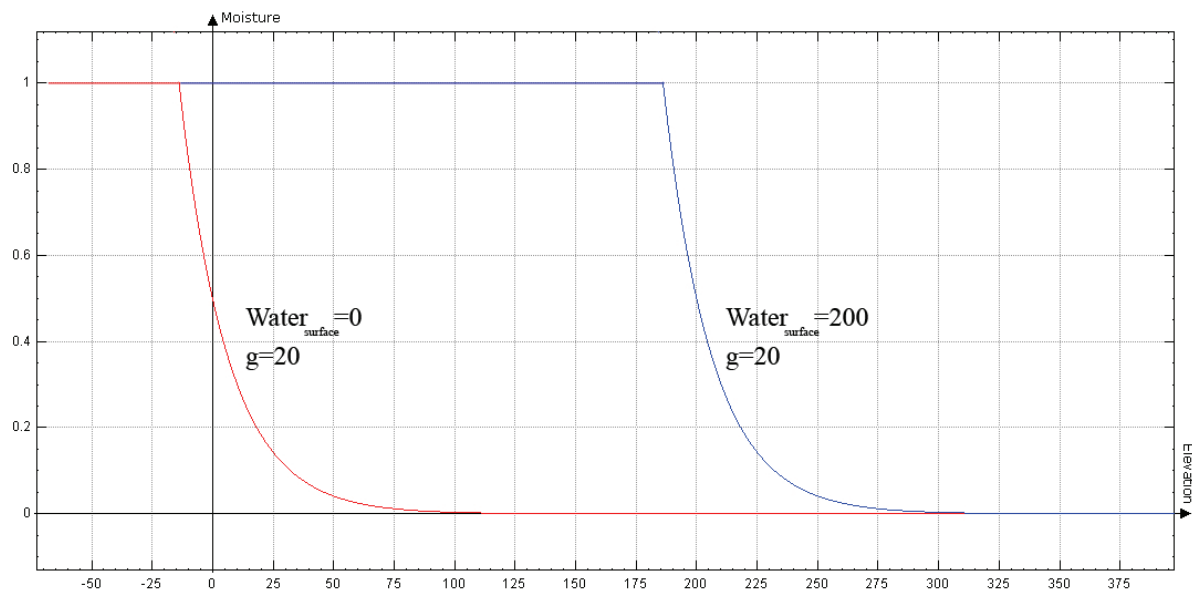


Figure 92. Hydrology Graph

4.4.2. Local Environment

The local environment in which a plant draws its resources from is derived from two main sources. The first is defined by the number of adjacent plants in the surroundings which affects the effective sunlight, shade temperature, space, and nutrient availability in a local area. The second condition uses Ground Info (4.2.4) as a source for effective soil acidity, soil depth, ground textures, and ground slopes.

4.5. Conclusion

Science in the past three centuries saw a mechanical approach in simulation and modelling characterised by linearity, repetition and predictability. Natural systems however, are nonlinear. This nonlinearity often leads to difficulties in study if traditional modelling methods are used. Observations showed that slight differences in the initial local condition of a natural system produces very different outcomes in the larger scope of the system. Similarly, changes in the interaction of smaller systems necessarily leads to variations in larger systems encompassing the smaller ones. This global outcome which issued from the local interaction of parts or of smaller systems has influenced the perspectives of modern science in its studies of natural phenomenon. Studies in Complex Adaptive Systems and Artificial Life in particular are new fields which

attempt to model natural phenomenon so that its principles may be understood and be used for problem solving. CAS and alife, and the principles behind them are what defines the concept of this, and of the rest of the chapters, which presents the major content of the thesis.

An Artificial Life model for synthesising vegetation and its ecology in a simulated world has been presented. In the first part of this chapter, an alife framework was developed, enabling research in experimental vegetation modelling. The framework consisted of a Virtual Environment integrated with the alife framework. The Virtual Environment, controlled by simulated natural factors affects the alife entities from settings interfacing between the *SeederManager* and the *SeederEngine* interfaces. An XML-based ecosystem blueprint was also developed for storing and describing the initial conditions of the VE.

The novelty of the VE and its implementation techniques has also been presented. These are algorithms for synthesising environmental variations, large timescale temperature variation, plant migration, ground info, segmentation, and plant species and dispersal statistics. Specifically, the segmentation algorithm, an optimisation technique has proven its effectiveness for speeding simulations of large numbers of interacting entities.

Using the principles of alife, a species-independent generalisation of a novel model of vegetation that can encompass all plant species has been developed. The rules within these alife agents are distilled from knowledge and observations of plant life and its ecology. These rules synthesise the lifecycle, preferences, and adaptability of plants. Also developed in the present research is the genetic makeup of plant species, described with an XML-based DNA structure. During reproduction, the genes are inherited by progenies. Variables of plant preference or tolerance towards environmental conditions, competition, and resource accessibility use real botanical properties acquired from various literatures. These are channelled through simple rules measured by the adaptability equation and the fitness function for determining the life and death of vegetation in the environment.

The next chapter verifies the rules of alife presented in this chapter and reviews the results via different experimental scenarios.

Chapter 5

Experiments with Vegetation Artificial Life

5.1. Introduction

Vegetation, similar to other organisms, persists on terrains based on niches of their abiotic and biotic environments. In Chapter 4, the methods for synthesising alive-based models of vegetation and its environment has been thoroughly defined. In this chapter the aim is to demonstrate that, via the process of macro self-organisation, these agent-based vegetation are capable of forming forest and undergrowth by means of their behaviour and the resources available in the ecosystem. In order to more accurately synthesise their collective behaviours, this chapter studies how vegetation patterns are formed locally via interaction and extra-locally via emergence in accord with their preference in various controlled environments. Furthermore, the use of real botanical parameters fine-tuned and regulated via simple rules in the approach could, in the near future, become a potential model for determining large-scale spatial and temporal distribution of dominant vegetation species, enhancing traditional methods and visualisation in studies related to forest dynamics and landscape archaeology. The benefits of synthesising vegetation behaviour using agent-based approach are constrained only by time. If the model is well defined, landscapes from the past, the present, and even the future can be simulated and forest formation in relation to climate changes predictable for benefiting studies related to forest planning, ecological models and even landscape architecture.

The way different plants colonise a landscape possesses different characteristic patterns. Such patterns can be observed in abundance in nature. Ferns appear to cluster together in abundance around damp landscapes and the growth of certain species of cactus is sparse in dry deserts. In a pine forest, the pine species are grouped together in sparse distances with an undergrowth of shade tolerant species. Willows are observed to grow near water sources. The environment plays an important role in the colony of plant species. Rising temperatures such as global warming may result in the extinction of species if they cannot adapt to the changes or if their migration is

hindered. In order to verify the alife vegetation in comparison to their nature counterpart, it is necessary to observe such characteristic patterns in the Virtual Environment.

In order to prove the concept, the alife algorithms can be applied to many different experimental scenarios. The experiments in this chapter focus on a particular Mesolithic environment – the Shotton River Valley. In Chapter 3, an archaeological perception of the river valley with its associated climate, environment, and vegetation have been given. This information is used throughout the study for verifying the algorithms. The experiments are conducted via an incremental process of space and complexity, carried out via a gradual build-up of terrain size, ecological factors, and interspecies biotic and abiotic interactions. Early experiments study plant fitness from the outcome of interaction between similar and dissimilar species on patches of landscape from the river valley. Experiments in the later stages introduce more species with different preferences and characteristics on larger terrains. The belief is that if vegetation behaviours can be verified in smaller settings, the incremental build-up of complexity over space and time should provide a credible means for simulating forest dynamics and landscape reconstruction. This is the bottom-up approach of Artificial Life research.

5.2. Vegetation Behaviours

The dynamics and fitness of individual vegetation behaviour can be observed within the Artificial Life Virtual Environment. The behaviours can be studied using an indicator for displaying their fitness in relation to competition for space, sunlight, and the environment. The collective dynamics can also be observed via the ecosystem boundaries demonstrated in the reproduction and distribution of species across different landscapes. This section looks at experiments conducted for verifying the alife algorithms in the Chapter 3.

5.2.1. Competition for Space

Figure 5.1 shows a scenario with three settings (*a*, *b*, *c*) containing three plant representations of the same species but with different age and sizes. Figure 5.1a is a scenario with crowd tolerant plants, 5.1c contains crowd intolerant plants, and the plants in 5.1b possess a level of crowd

tolerance intermediate between a and c . Table 5 lists the tolerance levels of each species in the ‘space’ gene of their DNA structure.

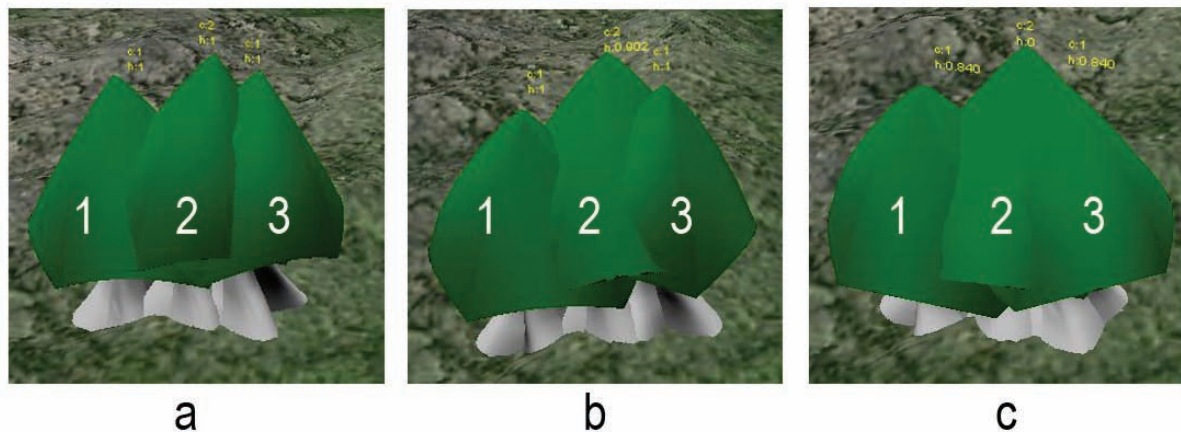


Figure 93. Fitness studies of competition between the same species with different age and sizes

Table 5. Genetic makeup of plant adaptability to crowd

Plant Types	Lower	Preferred	Upper
Crowd Tolerant	0.0	0.55	0.98
Intermediate	0.0	0.3	0.68
Crowd Intolerant	0.0	0.15	0.32

In Figure 93a, plant 2 have two competitors while plant 1 and 3 both compete with plant 2. Since plants in this setting are highly tolerant to crowded situations, their fitness levels are all full (1.0). The scenario in Figure 93b is a similar setting containing plants with intermediate tolerance to crowded space. In this setting, plants 1 and 3 have full fitness level. The fitness of plant 2 however, is slightly lower at 0.902. The setting in Figure 93c contains plants intolerant to crowd. Plant 1 and 3 both compete with plant 2 each having a fitness of 0.84. Plant 2 having two competitors yielded a fitness of 0.0 (dead).

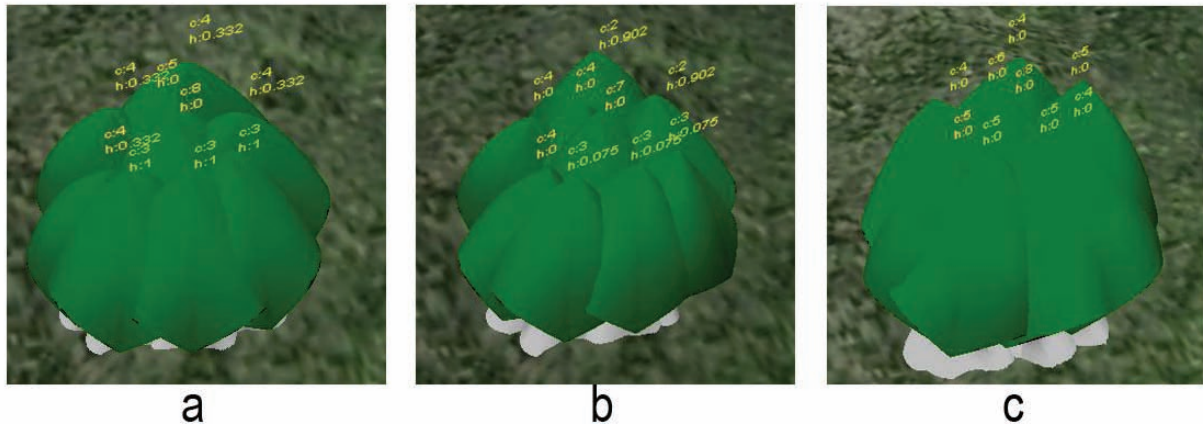


Figure 94. Fitness studies of competition between the species with the same age and sizes

Figure 94 is a larger scenario with three different settings containing plants adaptable to crowd (a), plants possessing an intermediate adaptability to crowd (b), and plants intolerant to crowd (c). The species possess the same DNA structures as those in the previous experiments (Table 5). In *a*, plants having more than five competitors showed a fitness of 0.0 (dead). Plants having four competitors yielded a fitness of 0.332 and plants having less than three competitors showed full fitness level. In setting *b*, due to the intermediate crowd adaptability of the plants, their fitness is relatively low in comparison to *a*. In this case, plants having three competitors yielded a fitness of 0.075 whereas plants having two competitors yielded a fitness of 0.902. The plants in setting *c* have all died due to its inadaptability to crowd. Figure 95 is the same scenario with large clusters of different vegetation types competing for space.

Their genetic preferences of each species for space are shown in Table 6.

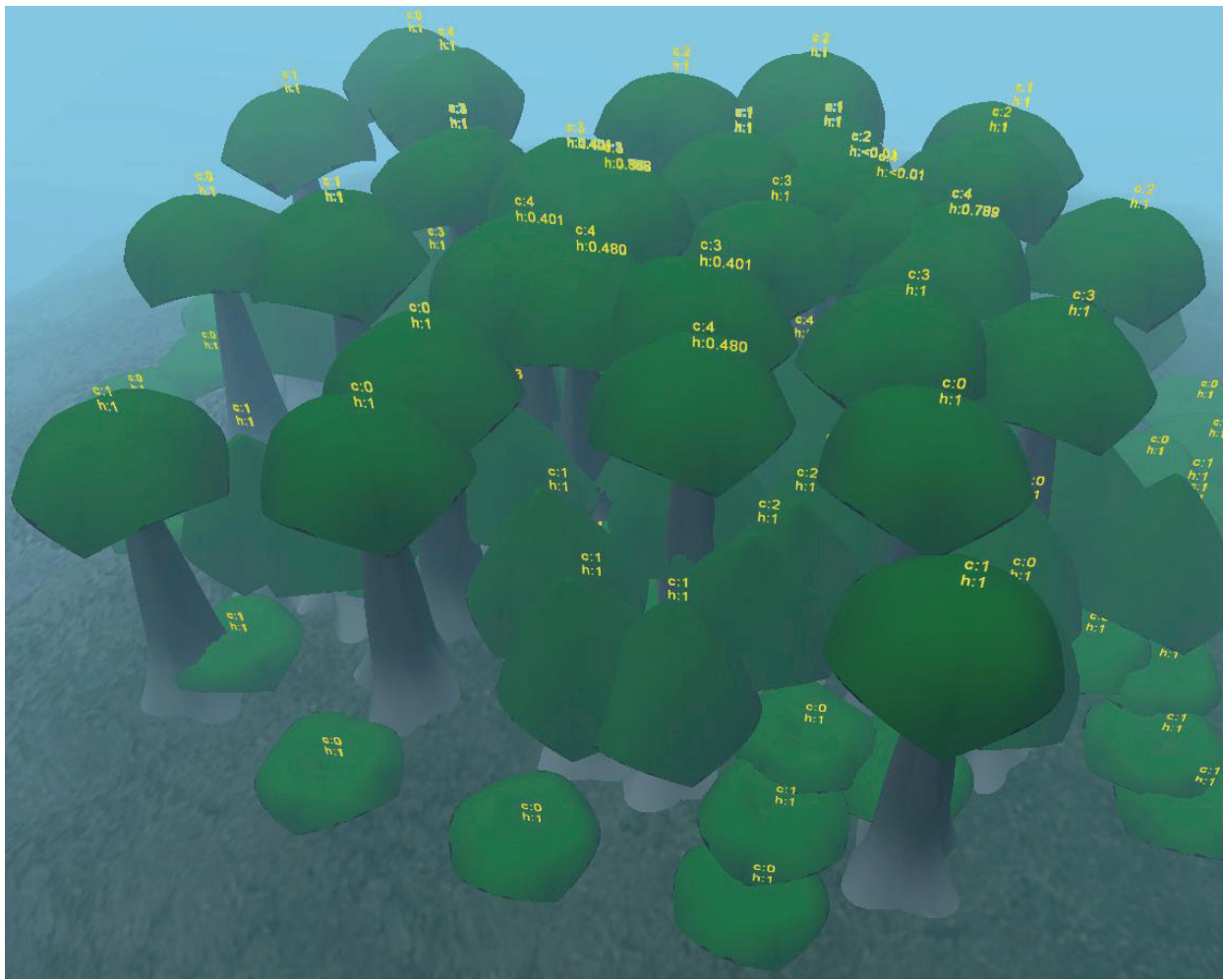


Figure 95. Fitness studies of competition between different species of plants

Table 6. Genetic preferences of different vegetation types to crowded settings

Plant Types	Lower	Preferred	Upper
Crowd Tolerant	0.0	0.15	0.32
Intermediate	0.0	0.3	0.68
Crowd Intolerant	0.0	0.55	0.98

The scenarios above have demonstrated the main concept of the Artificial Life model developed in Chapter 4. In the scenarios, each plant senses its environment for competitors. The shapes and sizes of each plant directly affects the plants it is competing with and their genetic makeup influences their overall fitness over time. The fitness of these plants uses the fitness function measured through the adaptability formula covered in Chapter 3. The figures shown above (Figure 93-Figure 95) are snapshots at particular time intervals for demonstrating the concept. It is important to note that the fitness of each plant changes at different stages of growth and snapshots taken a few simulation steps later may reflect different levels of fitness.

5.2.2. Competition for Sunlight

Plants compete for sunlight if their canopy distances between each other are overlapping. Taller plants with larger canopies have more advantage over sunlight whereas smaller plants in the undergrowth receive less. Plants growing under large trees could seriously impede their growth if they have low adaptability to shade. Figure 96 is a scenario where groups of plant representations of trees, shrubs, and herbs clustered together in a sparse setting. The competition indicator (c:0) of the taller trees showed no competitors. The level of sunlight at 0.6 units also matches their preference and the measure of the two factors yielded a full fitness level for the trees. Smaller trees however, are at a disadvantage. Two smaller trees at the centre foreground with the same age and preferences showed different fitness levels. The small tree at the left (1) without any competitor has full fitness. The tree to the right (2) having three competitors has a fitness of less than 0.01. The shrubs shown in the figure possesses different adaptability to sunlight in their genes. Shrubs not in the shade have a fitness level of 0.829 (e.g., 3) while shrubs having a single competitor (4) yielded different fitness levels depending on the type, height, and size of their competitors. Herbs in this scenario have a lower tolerance to strong sunlight; this also means that they are shade tolerant. In this scenario, the herbs have a fitness of less than 0.01 due to strong sunlight (0.6 units). However, when the level of sunlight has decreased to 0.4 units, herbs without competition have a fitness level of 0.894 (Figure 97). If the canopy of trees shades the undergrowth (1 and 2 of Figure 97), the effective sunlight is decreased to a level ideal for the herbs (yielding a fitness of 1.0). A shrub (3 of Figure 97) also found the level of sunlight ideal for its growth. The genetic makeup of these vegetation types are shown in Table 7.

Table 7. Genetic makeup of plant adaptability to sunlight and shade

Plant Types	Lower	Preferred	Upper
Tree (Shade Intolerant)	0.45	0.65	0.98
Shrub (Intermediate)	0.22	0.46	0.79
Herb (Shade Tolerant)	0.0	0.3	0.6



Figure 96. A scenario showing representations of different vegetation types competing for sunlight

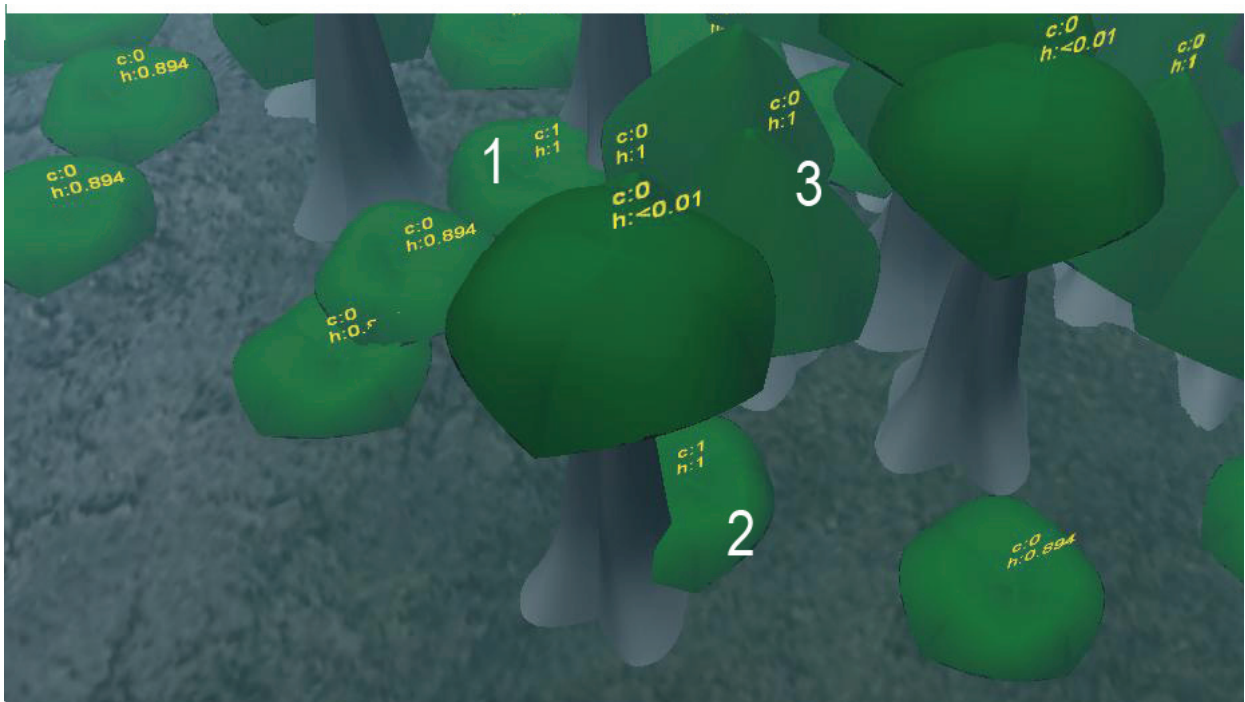


Figure 97. A closer look at the same scenario showing the fitness of different plants under another level of sunlight

5.2.3. Behaviours on Soil Moisture

In the physical world, some species are distributed near sources of water whereas others appeared in dry terrains. These differences in habitat are based on their adaptability to hydrological conditions. In this experiment, plants are initially scattered randomly across the terrain (Figure 98a). After a few simulation steps, plants unable to adapt to their local condition dies, leaving adaptable species on different patches of the terrain (b). It can be observed that the boundary of blue plants is limited to the island where the soil moisture content is at the highest. The population of the blue species are rather small due to the limit of their ecological niches. Green plants are sparse having boundaries near the river banks of the terrain. This is due to its adaptability to intermediately dry conditions. In the scenario, the yellow species possess the most adaptable genetic constitution, making it the fittest species able to adapt to both wet and dry conditions. The habitat of the yellow species spans the entire landscape. In the long run, the yellow species will outnumber the other species and drive them off the boundary of the terrain. The genetic make of these species are shown in Table 8. The inset shows an outcome of a stricter rule for tolerance with species hardiness in the adaptability equation (4.3.8) set to $b=0.3$ as compared to $b=0.5$ used in the simulation in Figure 98a and Figure 98b. A stricter rule of measure in each plant sets a clearer ecotone for the species. Ecotones and ecoclines will be covered later in the chapter.

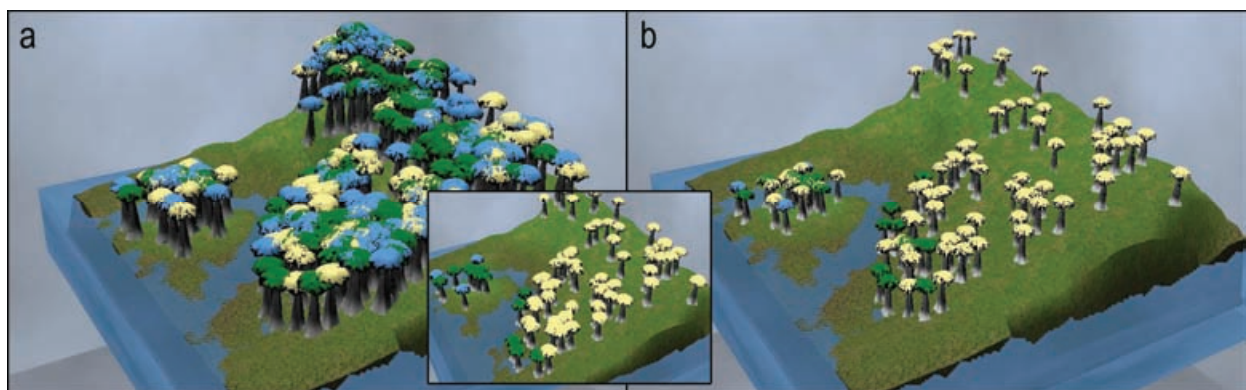


Figure 98. A scenario where plants with different moisture preferences are distributed across a landscape (a), the outcome (b) after a few simulation steps, and the outcome of a stricter rule (inset) showing clear ecotones

Table 8. Genetic makeup of plant adaptability to soil moisture

Plant Types	Lower	Preferred	Upper
Yellow (Intolerant)	0.02	0.28	0.67
Green (Intermediate)	0.13	0.43	0.82
Blue (Tolerant)	0.3	0.58	0.96

5.2.4. Behaviours on Temperature Extremes

Different types of vegetation thrive in different climates and altitudes. The experiment in this section simulates temperature extremes in a strip of landscape 288.5m in elevation measured from below sea level. Temperature and altitudinal ratio in the Virtual Environment is set to decrease by -7°C over 100 metres in elevation instead of the normal -0.6°C . Summer temperatures at sea level can be as high as 28°C and during winter can be as low as -0.5°C . At the mountain regions, summer temperatures averages 8°C and winter at the highest point can be as low as -20°C . Three species of plants adaptable to extremes of cold and hot temperatures were randomly distributed across the mountain strip. The landscape is divided into five divisions of approximately 48m each beginning from the sea level for measuring the population of each species. Figure 99 are selected screenshots showing the high-altitude terrain in different time-sequence from year 3 (T3) to year 34 (T34). A chart reflecting the population growth and decline of the individual species in five different levels of elevation is shown in Figure 100.

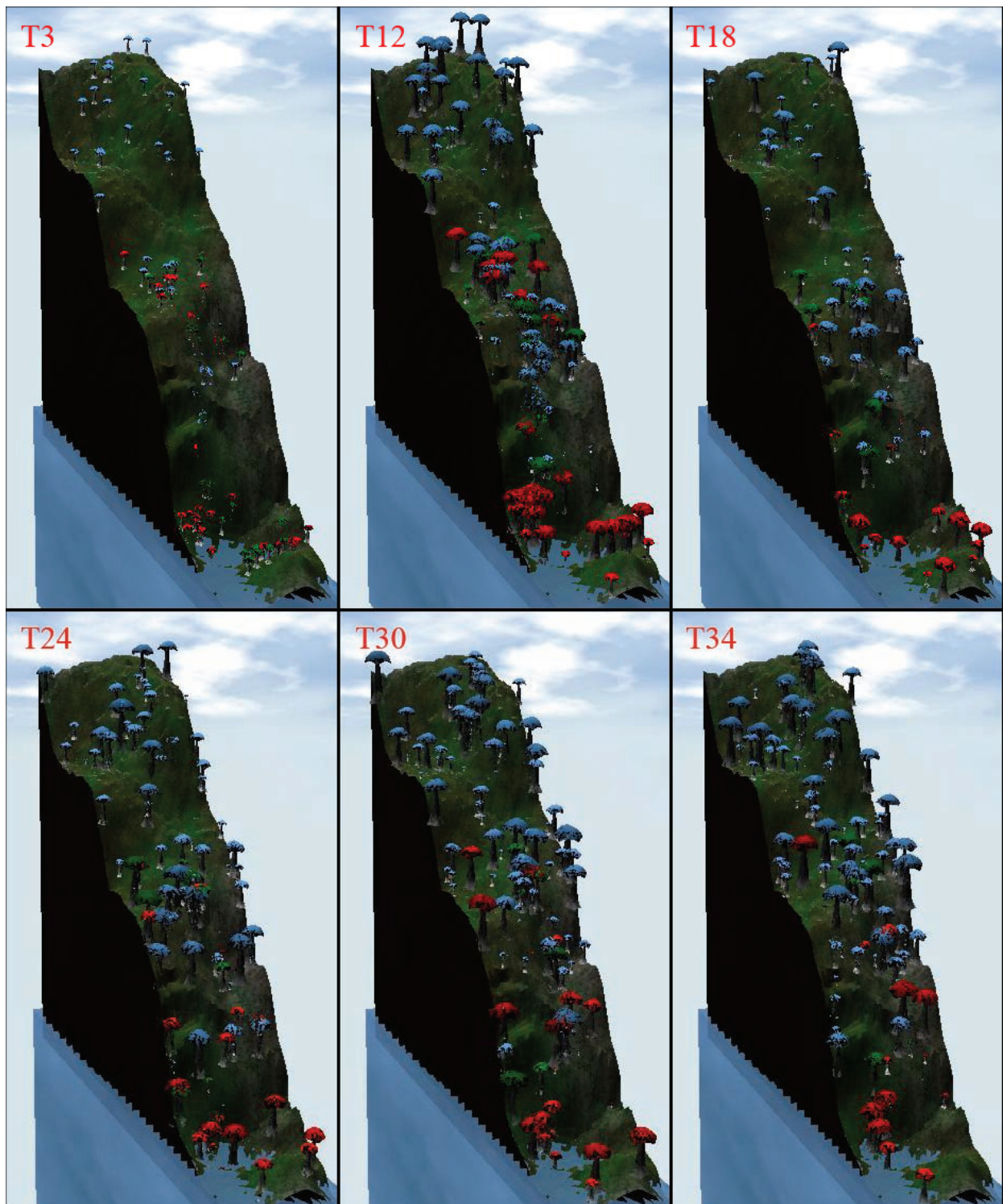


Figure 99. Population of species adaptable to extremes of temperatures in a high altitude terrain

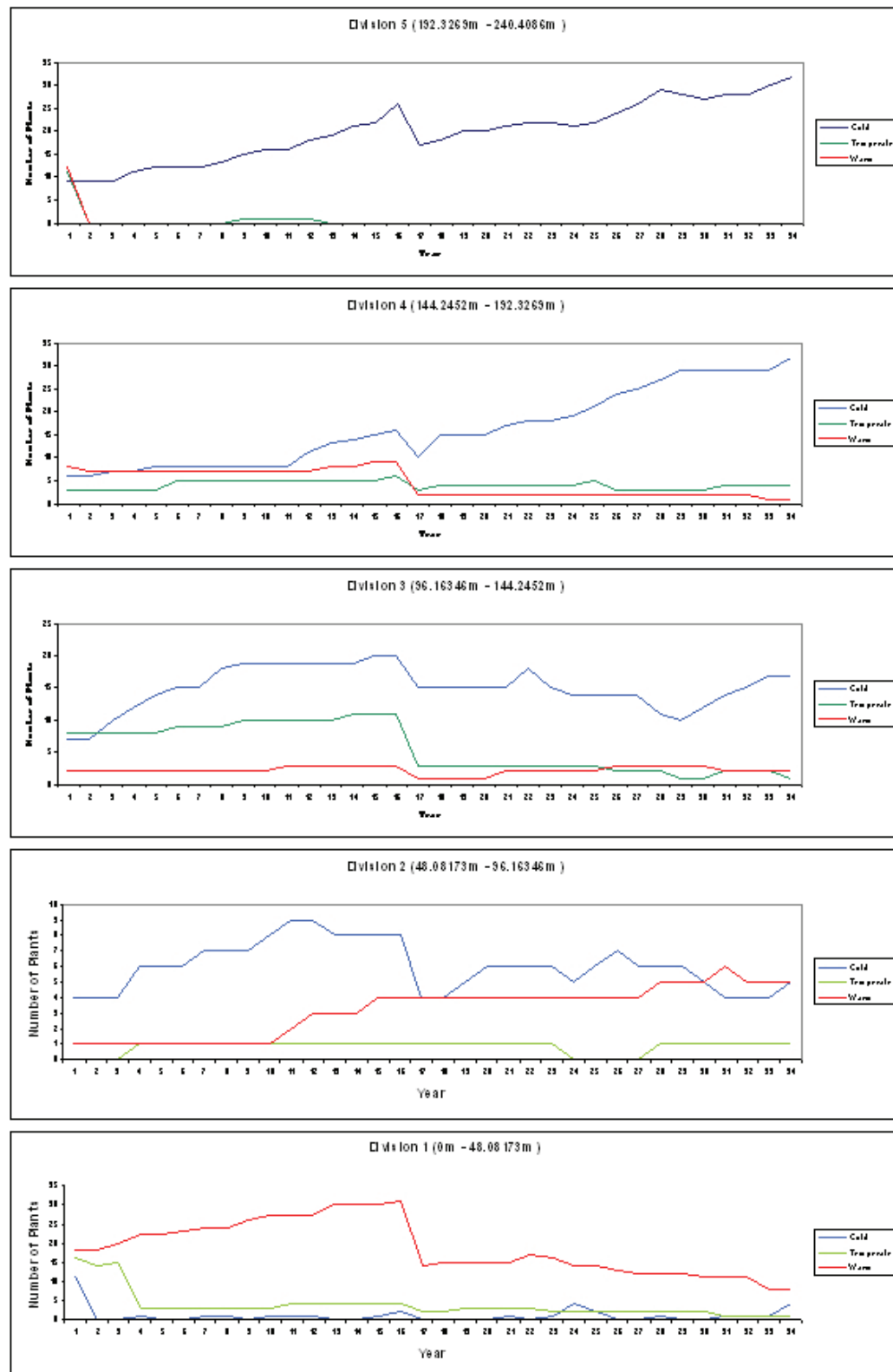


Figure 100. Graph reflecting population growth among three different species of plants adaptable to extremes of temperatures over five altitudinal divisions

The graph in Figure 100 demonstrates the ecotone of species, a term used by ecologists to describe the ecological niches of species adaptable to that specific condition. The population of the blue species showed a trend of growth towards the highest point (division 5) of the terrain where conditions are in the extremes of cold. In contrast, the niche of the red species is at the lowest point of the terrain with gradual decline in higher altitudes. The growth of the green species on the other hand, is at the peak in the middle section of the terrain with gradual decline towards the upper and lower altitude. The genetic makeup for resistance to temperature extremes of each of the species are listed in Table 9.

Table 9. Genetic makeup of plant resistance to extremes of temperatures

Plant Types	Lower	Preferred	Upper
Red (Hot Climate)	-15°C	8°C	25°C
Green (Temperate)	-7°C	10°C	27°C
Blue (Cold Climate)	-6°C	18°C	35°C

5.2.5. Behaviours on Soil Acidity

Soil acidity (pH level) is a very important factor affecting plant growth. The experiment below demonstrates plant adaptability to soil acidity. Three species of plants with different tolerance to soil acidity (Table 10) were randomly distributed across a terrain (Figure 101) with gradients of increment in soil acidity. Black areas contain high levels of alkaline (pH0) while white represents areas with the highest level of acidity (pH14).

Table 10. Genetic makeup of plant adaptability to different levels of soil acidity

Plant Types	Lower	Preferred	Upper
Red (High)	pH11	pH8	pH14
Green (Moderate)	pH4	pH7	pH9
Blue (Low)	pH0	pH3	pH5

T3 of Figure 101 showed a stable condition after the randomly distributed plants have settled in their ecological niches. At T10, each species begin populating the terrain. T19 depicts a time sequence where each species collectively discovers its own ecological niche, adapting to the local conditions. At T29, the population reaches a climax community, a condition characterised by stability in growth and species habitat.

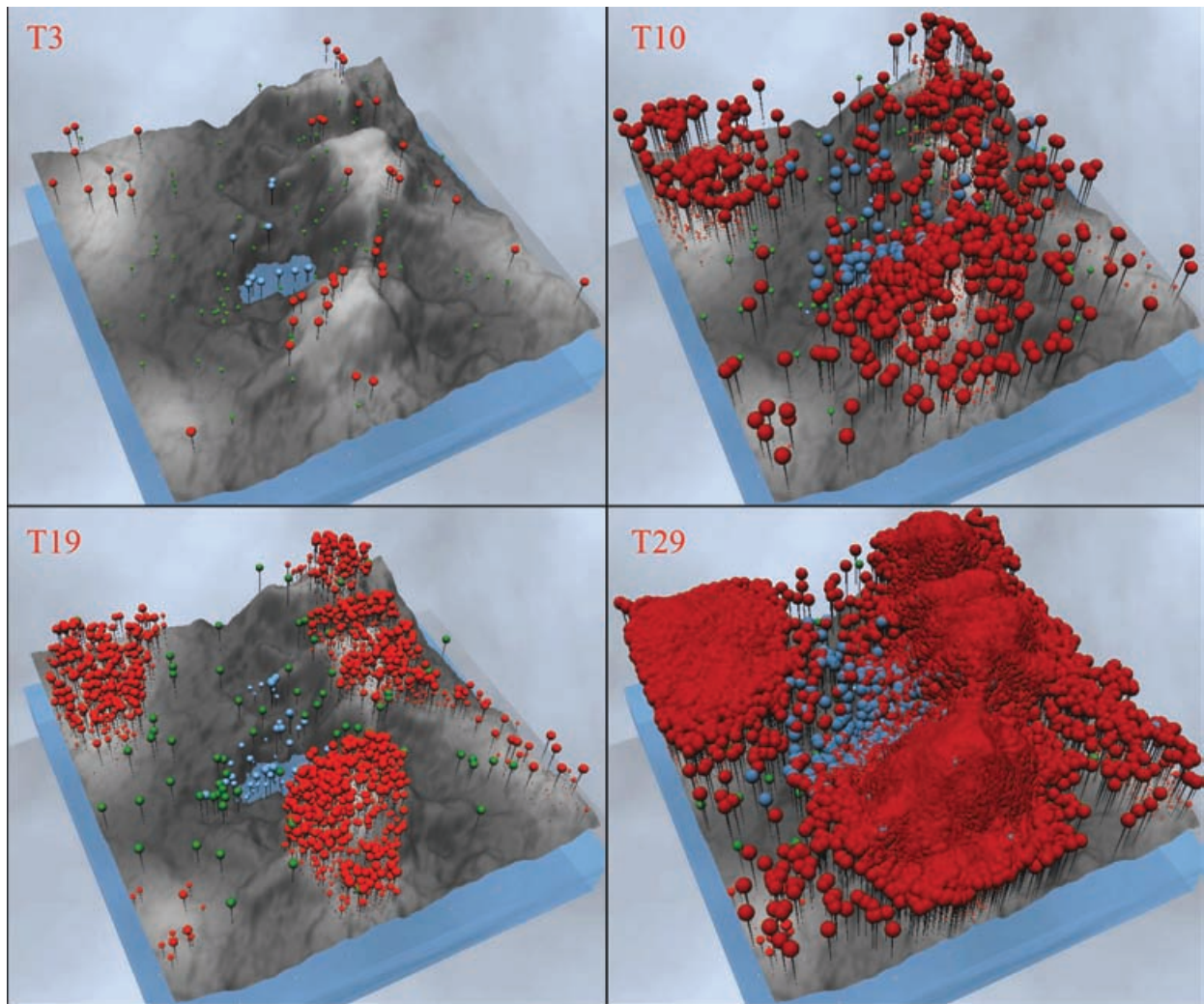


Figure 101. Time sequence of species adaptable to different levels of soil acidity

5.2.6. Behaviours on Soil Depth

In this experiment, three species of plants were randomly distributed across a terrain represented by a gradient of shallow soils (white regions) to deep soils (black regions). The red species is relatively adaptable to shallow soils, the green species with a moderate adaptability, and the blue species intolerant to shallow soils. In Table 11, the upper tolerance of all plants (shown as 1) is not measured (using the left bound adaptability function) as all plants are assumed to be adaptable to deep soils. In T1 of Figure 102, each species are randomly distributed across the terrain. T10 is an initial stable condition when vegetation intolerant to local conditions have died. In T18, progenies of each species can be seen to populate their ecological niche. T24 shows the climax community. The population of the red species is the highest as expected due to its

adaptability to all levels of soil depths followed by the blue species. The green species have the lowest population count due to competition from the red and blue species over available spaces.

Table 11. Genetic makeup of plant adaptability to different levels of soil depth

Plant Types	Lower	Preferred	Upper
Red (Shallow)	0.09	0.2	1
Green (Moderate)	0.3	0.5	1
Blue (Deep)	0.6	0.8	1

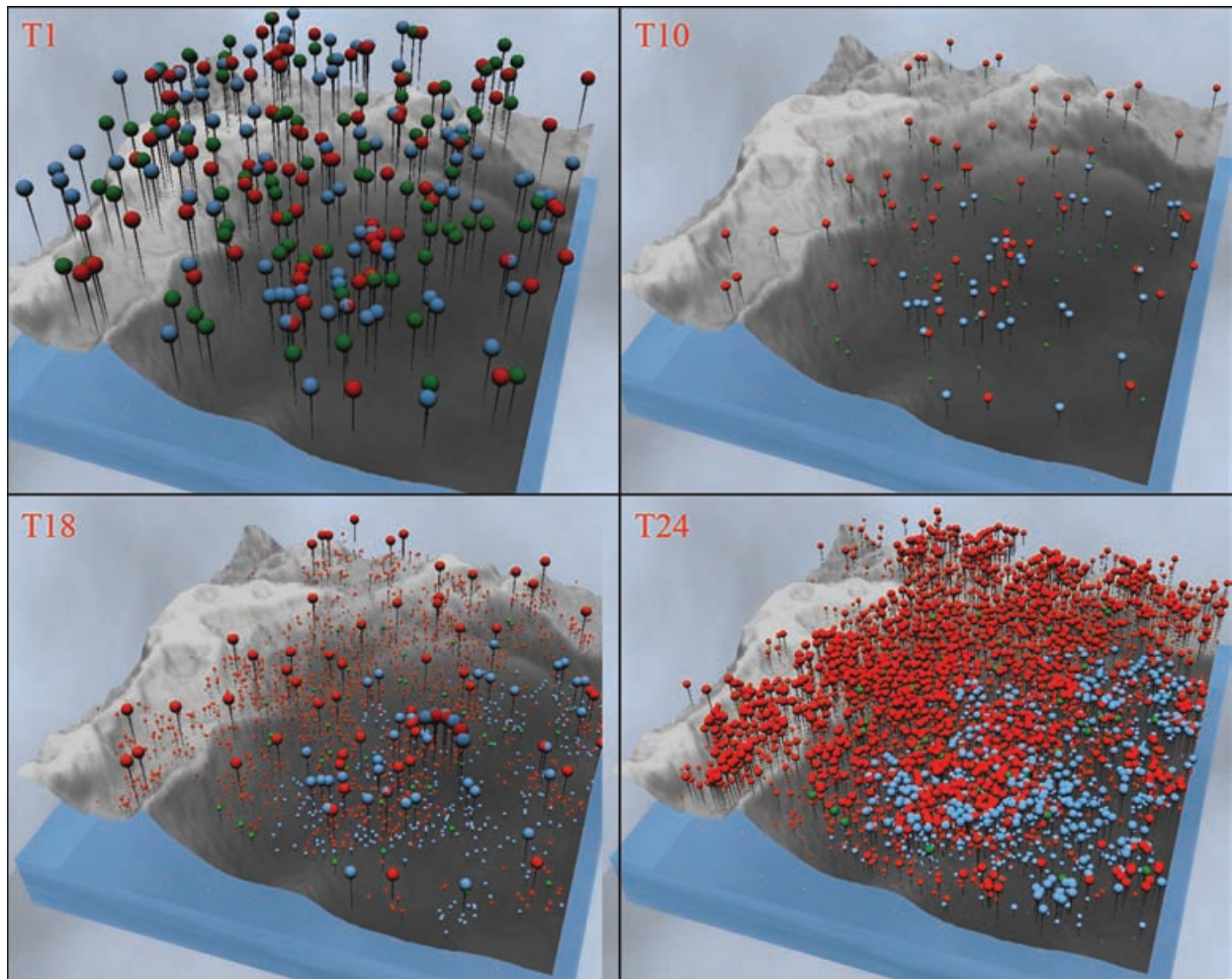


Figure 102. Time sequence of species adaptable to different soil depth

5.2.7. Behaviours on Generic Ground Info: Slope Conditions

This experiment uses the generic ground info to define slope angles on terrains. The genetic makeup of three different plants adaptable to levels of slope angles are defined in Table 12. The red species is the most tolerant to steep terrains followed by the green and blue species. Figure 103

demonstrates the patterns of growth on three different slopes on the terrain where the species are initially randomly distributed. Larger plants are oldest and parents to smaller ones. T1 is a stable condition after each species has found its own niche. T2 and T3 are sequences showing the population of each species in their respective habitat. In T4, the adaptability of each plant towards different slope conditions has become quite apparent. Due to its adaptability, the population of the red species are seen in all divisions of the landscape. It can also be observed that only the red species exists in the steep slopes. In the scenario, most of the green species populates the middle section whereas the blue species covers plots of flat lands in the terrain. Figure 104 are three graphs reflecting the population growth of each species on the divisions of the landscape.

Table 12. Genetic makeup of plant adaptability to different levels of slope angle

Plant Types	Lower	Preferred	Upper
Red (Steep)	20°	70°	83°
Green (Moderate)	20°	45°	55°
Blue (Low)	0°	15°	35°

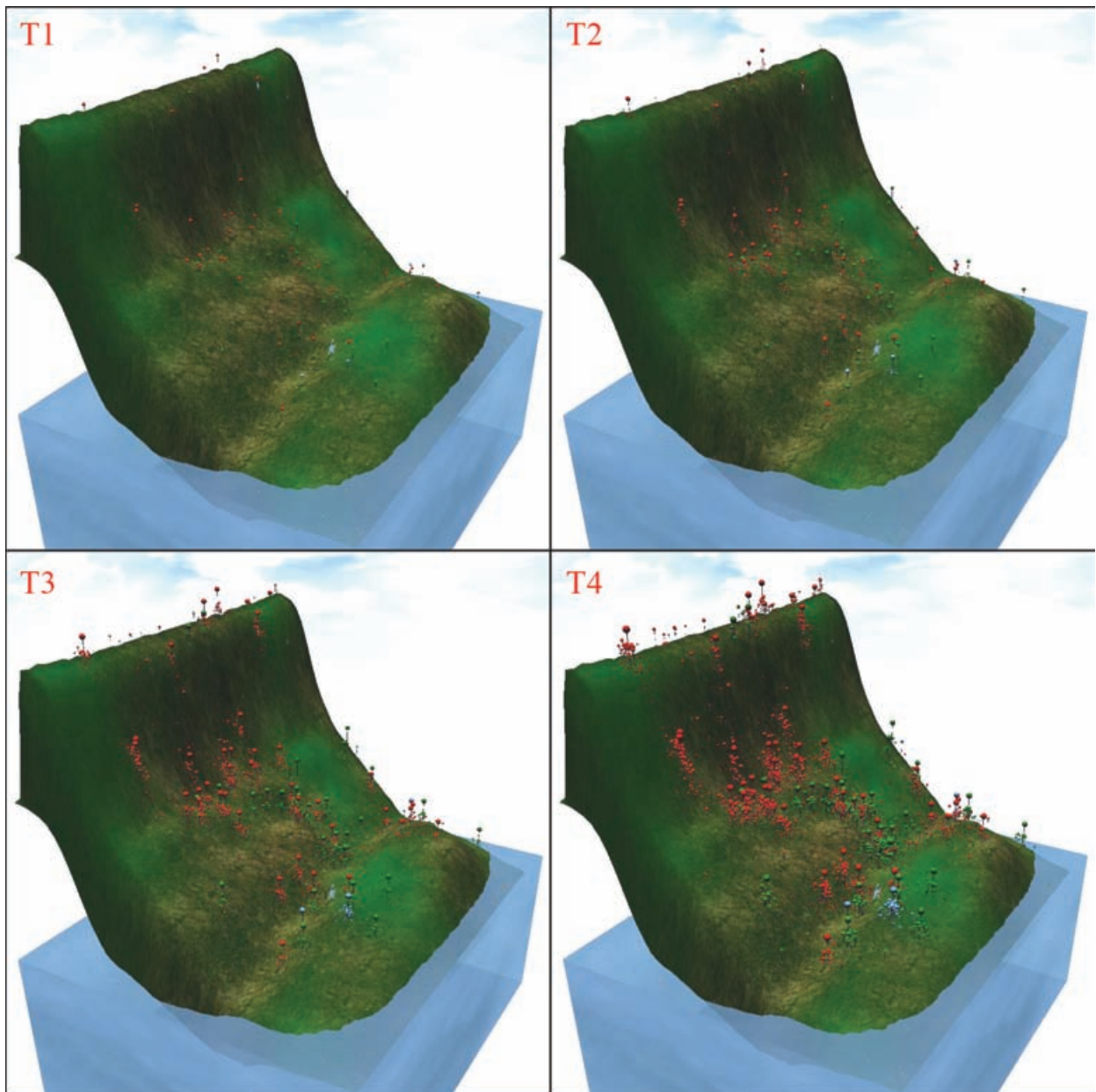


Figure 103. Time sequence of species adaptable to different terrain slopes

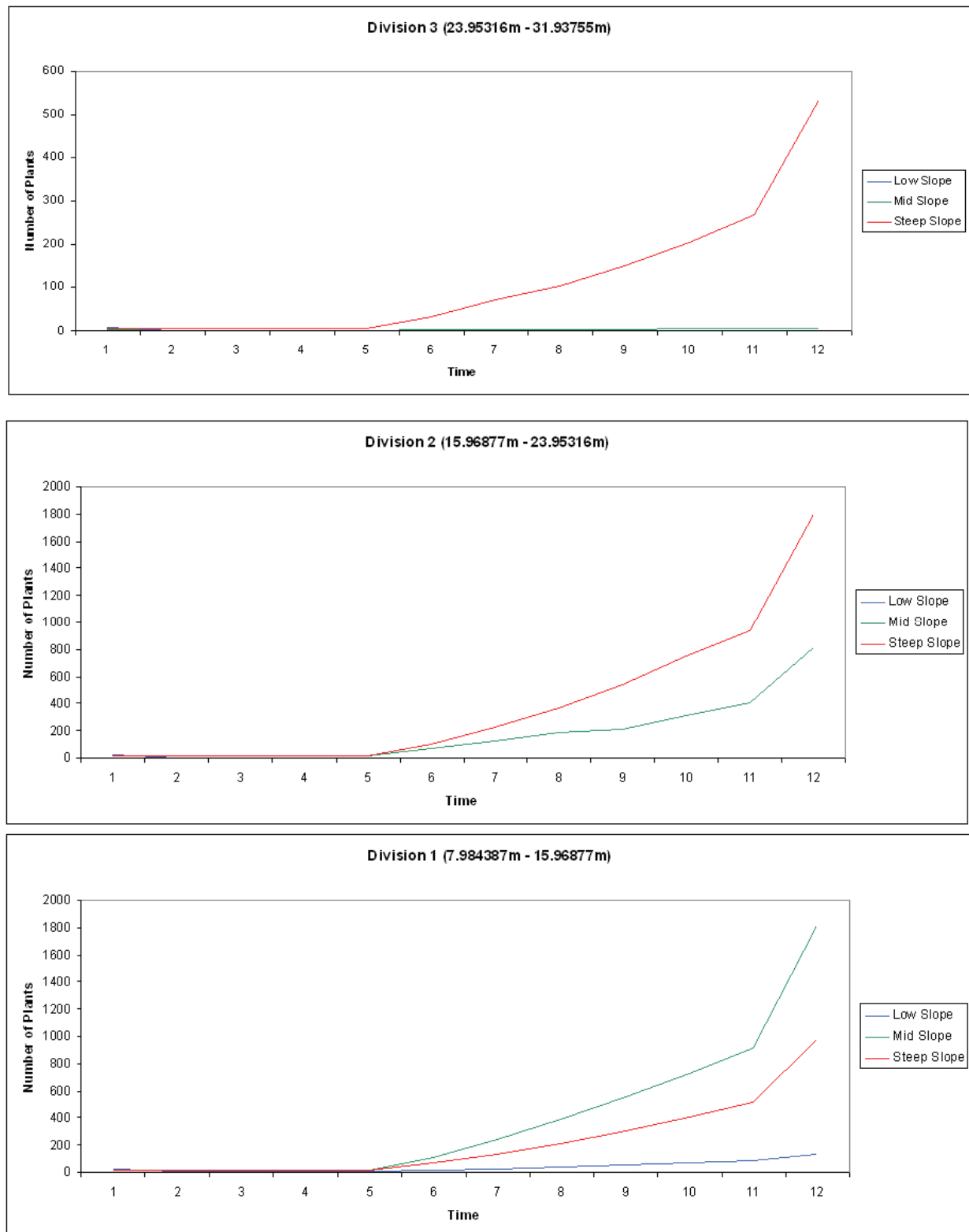


Figure 104. Species concentration in different slope conditions

5.2.8. Layered Studies on Soil Types: Acidity, Depth and Texture

A scenario is created for testing species population on habitat based on different conditions of soil types. Three different soil types – soil acidity, soil depth, and soil texture were added into the factors affecting the plants in order to observe their behaviours. Higher concentration of whites yields higher values for each respective soil conditions. The soil layers represented as concentration maps are shown in Figure 105. Competition for space is also part of the equation. The genetic makeup for each species is shown in Table 13-Table 16.



Figure 105. Concentration maps representing soil acidity, soil depth, and soil texture

Table 13. Genetic makeup of plant adaptability to different levels of soil textures

Plant Types	Lower	Preferred	Upper
Red Species	0.3	0.8	0.95
Green Species	0.3	0.5	0.75
Blue Species	0	0.25	0.5

Table 14. Genetic makeup of plant adaptability to different levels of soil acidity

Plant Types	Lower	Preferred	Upper
Red Species	0	4	8
Green Species	4	7	9
Blue Species	6	11	14

Table 15. Genetic makeup of plant adaptability to different levels of soil depth

Plant Types	Lower	Preferred	Upper
Red Species	0	0.2	0.7
Green Species	0.09	0.2	0.4
Blue Species	0.4	0.8	1

Table 16. Genetic makeup of plant adaptability to crowded spaces

Plant Types	Lower	Preferred	Upper
All Species	0	0.35	0.5

In the simulation, all species are distributed evenly across the landscape. T3 in Figure 106 shows an initial stable condition when the plants have found their niche. T10 shows the growth and population increase of existing species. In T17, the population has increased and the progenies of each species are beginning to spread into habitable niches. T22 is a condition prior to climax community. The distribution of species continued into habitable regions. Figure 107 is a population graph reflecting the growth of each species.

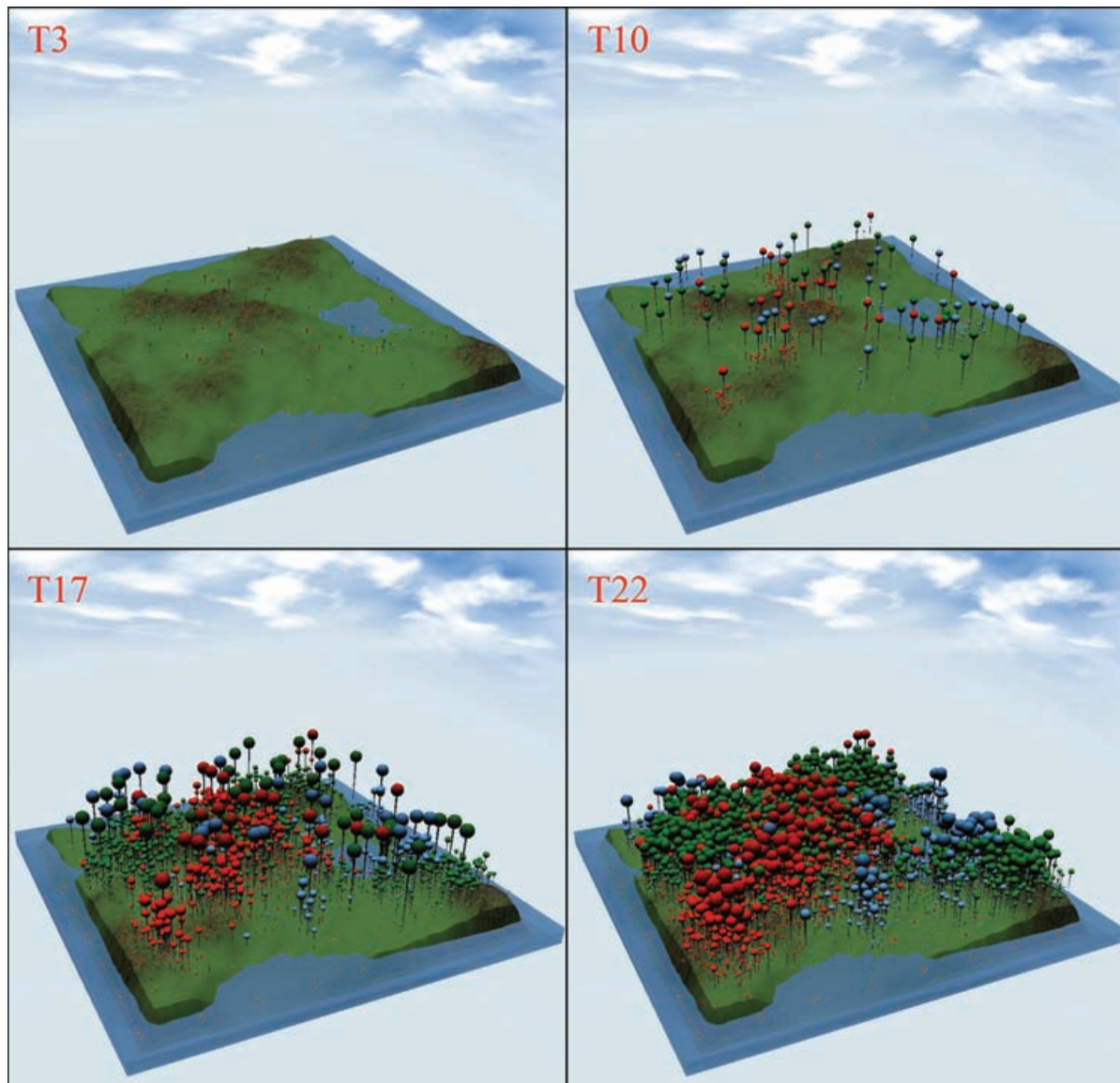


Figure 106. Time sequence of species adaptable to soil acidity, depth, and texture

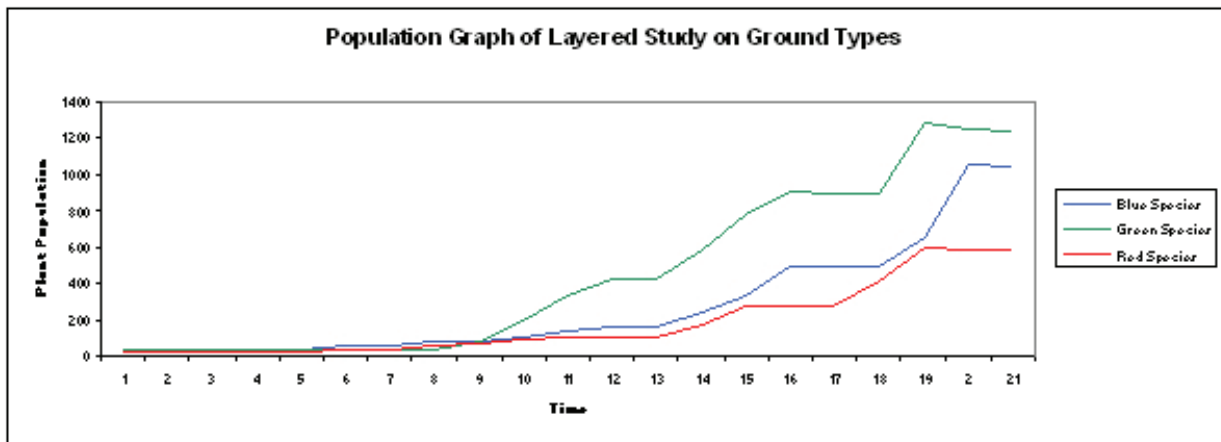


Figure 107. Population graph depicting the growth rate of each species in the layered study

5.3. Effects of Environmental Factors on Vegetation Model

A merge of environmental factors affecting individual plants is needed to verify the model defined in Chapter 4. This section presents experiments conducted with vegetation constituted with real botanical parameters channelled through simple rules measured by the fitness function. 3D vegetation representations are modelled based on real plants. The studies are conducted using partial or full environmental parameters for the purpose of elaborating the importance of each factor.

5.3.1. Reproduction, Seed Germination, and Crowd Tolerance

In this experiment, *Dryopteris filix-mas* (Male Ferns) and their spores were released onto a 5m² sampling of the river valley test bed for observation (Figure 108). The adaptability of the Ferns can be seen in Table 10. The ecosystem conditions were set to be favourable to the growth, reproduction, and germination of the Fern species. T1 is the initial setting where some of the Ferns can be observed. In T2, The growing Ferns began reproducing with some of the spores being dispersed around the terrain. From T2 onwards some of the offspring have germinated due to favourable conditions from the soil, temperature, sunlight, and moisture. The adaptability of the Male Fern species towards crowded setting can be seen in T5-T6. From T6 onwards the emerging patterns arrived at a stable condition with very minor variations in the changing patterns.

Preferences of the Ferns are according to the values in Table 17. Figure 109-Figure 111 demonstrate various species with different levels of tolerance to crowd.

Table 17. Genetic makeup of species adaptability for *Dryopteris filix-mas*

Condition	Lower	Preferred	Upper
Sunlight	0.39	0.56	0.69
Temperature	-4°C	20°C	32°C
Moisture	0.08	0.21	0.62
Space	0.07	0.84	0.98

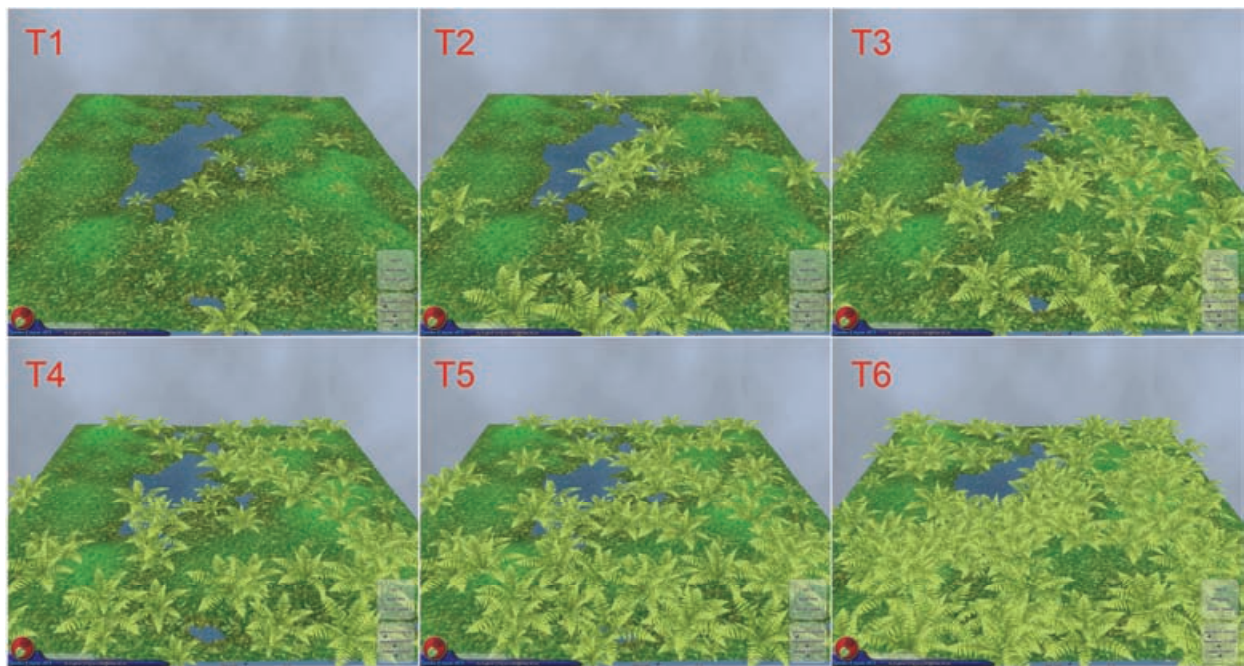


Figure 108. Growth of the Male Fern species

In Figure 109, the pine species grows at a rather sparse condition in comparison. Beginning from T23, smaller and weaker Pines die from competition from sunlight and space as the trees reproduce and grow (T55). At T86, a comfortable Pine forest emerged. Young Pine trees can also be observed to thrive at open spaces where taller trees are sparse.



Figure 109. A Pine landscape showing the density and pattern of growth

Figure 110 is a similar scenario planted with Oak trees. Oaks by nature grow much further apart due to its broad shape and intolerance to crowded space. As the trees grow, smaller and weaker Oaks are gradually replaced by larger ones.

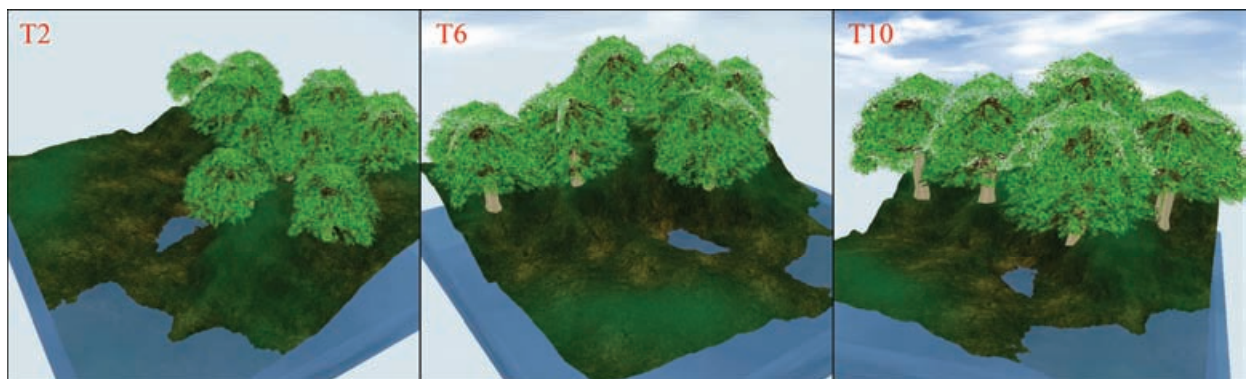


Figure 110. An Oak landscape showing the density and pattern of growth

Figure 111 shows a Hazel landscape. The Hazel seedlings grow comfortably in T2 without competition. In T24 however, the setting has become denser. At T40, the water level is lowered to allow the seeds to spread in the foreground. At this stage, the shrubs have occupied all available spaces, leaving no space for the growth of younger plants.



Figure 111. A Hazel landscape showing the density and pattern of growth

5.3.2. Environmental Changes and Migration

In this experiment, the topology of the Virtual Environment as a landscape is defined so that it increases in elevation towards the far plane. This implies that, as we approach the top of the landscape, the temperature decreases proportionally at 0.6°C per 100m in Mesolithic times [273]. Figure 112 is a representation of the fitness and location of different species of plants (red, green, yellow, blue, and orange) in a two-dimensional virtual space. The plants are represented as circles for a clearer view of the patterns with older plants as larger circles and fitter plants with more leaves. T1-T8 are screenshots from variable time steps. Table 18 shows the temperature preferences for each species.

Table 18. Genetic makeup of plant adaptability to temperature

Plant Types	Lower	Preferred	Upper
Red	5	13	19
Green	4	7	9
Yellow	9	10	13
Blue	8	15	25
Orange	15	23	26

At T1, each species begin producing offspring. At T2, parent plants and some offspring begin to die (turning white) as a result of the environment and competition. Where conditions are favourable to the vegetation, an increase in reproduction is observed in T3, clothing the landscape with offspring. From T4-T6, we gradually increase the global temperature and in response the plants begin to migrate north due to the simulated effects of global warming. From T7-T8, the vegetation moved southwards as the global temperature dropped. The emerging patterns have reached a stable condition in T8 where the “face of nature remains uniform” as described by

Darwin's observations of life in the *Origin of Species* [186]. In the experiment, a species of vegetation (orange) is dominant due to its adaptability and advantage over the open space. In temperature variations, the yellow species (in T6), and the green and blue species (in T8) are observed to reach a relatively low quantity due to its inability to tolerate changes and the invasion of the more dominant species.

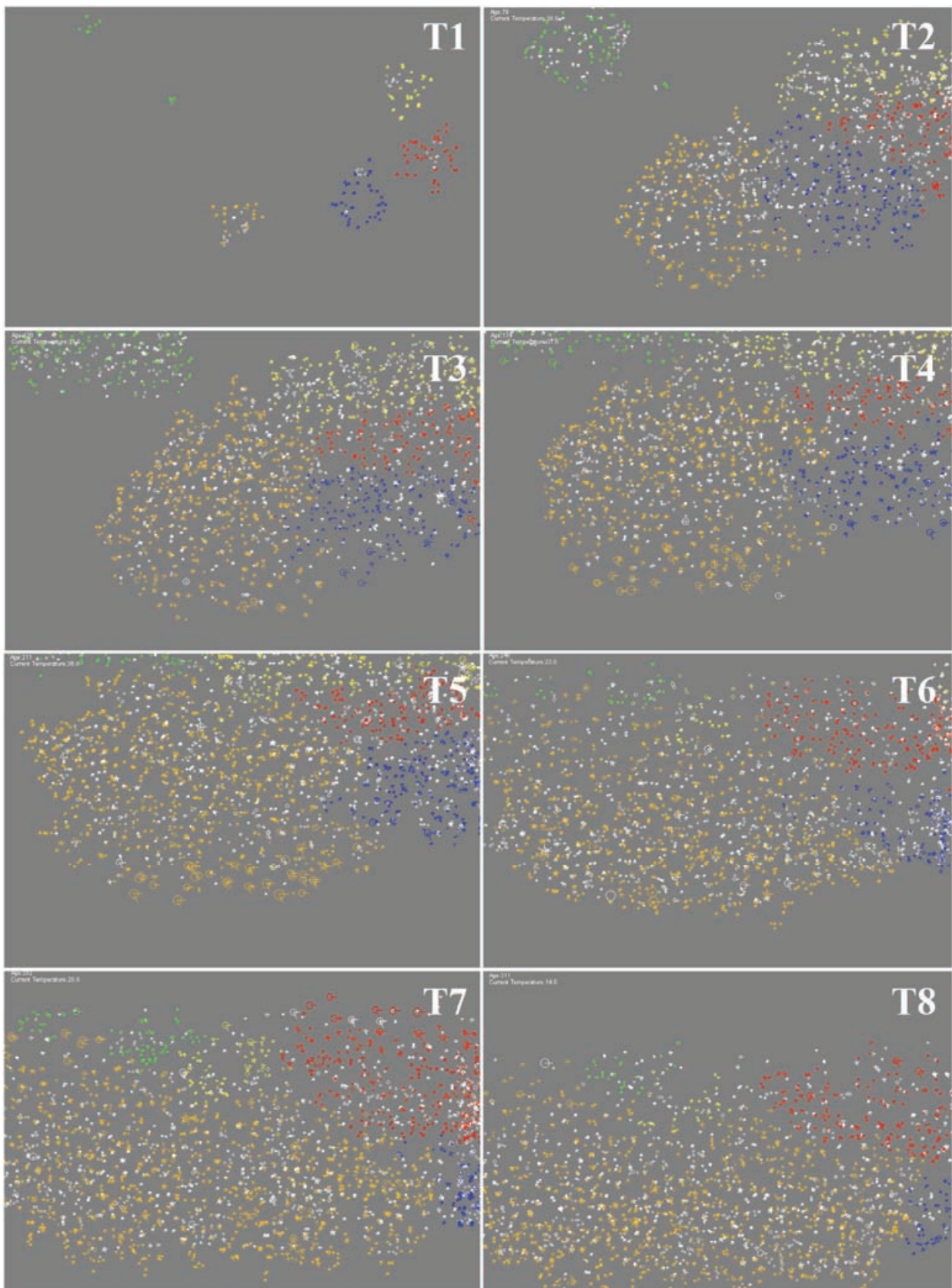


Figure 112. Population graph depicting the growth rate of each species

5.3.3. Growth and Competition

A terrain sampled from the Shotton River Valley with the size of twenty metres in width and length with a maximum elevation of one metre was established in the second experiment. The size of the landscape was deliberately reduced to the specified size for the purpose of simulating the competition among plants of different species and the level of growth. Four species of plants were released onto the landscape with different age groups from seed/spores to young plants. Figure 113 are screenshots from a variable time steps T1-T15 of a total of 160 years. T1-T12 is a 100 years. Environmental conditions were set to a four seasonal cycle with ecological signals defined in Section 4.5. Initial 3D representations of vegetation of different ages were placed in the landscape using the *SeederManager* before launching the engine for the experiment. *Pinus Sylvestris* (Pine), *Salix Babylonica* (Willows), *Corylus Avellana* (Hazels), and *Dryopteris filix-mas* (Male Ferns) of different ages were situated around the landscape. A young Pine tree can be seen in T1. In the inset (a), seedlings begin to appear around the landscape. In T2, the Willows and the Hazel have grown to maturity. The plants continue to thrive around the landscape due to the availability of resources such as space, sunlight, and nutrients. In T4-T5, the Willows have grown larger and more Hazels have appeared. All the plants continue their reproduction by dispersing their seeds across the terrain. In T5, more Pine seedlings (also in inset c) have germinated, of which some died later due to lack of resources. Two young Pine trees can be seen (inset b) under the Willow tree on the right. In T6, the Pine trees have reached the height of the willow. In T7-T8, the Willows died due to old age. The landscape has become denser in T9 as growing trees occupy more spaces, leaving little space for the younger plants to develop. Inset d showed some young Pines developing more quickly. From T10-T12, some Hazels reached their maximum lifespan and died, the Pines are developing well at this stage. More Ferns begin to appear in T10. At 127 to 160 years from T13-T15, the landscape is predominantly of Pine and Hazel. The plants continue leaving offspring in the landscape (inset f), beginning yet another cycle of Artificial Life.

The genetic makeups of the species used in the test are defined in the tables below.

Table 19. Genetic makeup of species adaptability for *Pinus Sylvestris*

Condition	Lower	Preferred	Upper
Sunlight	0.4	0.5	0.7
Temperature	-20°C	20°C	35°C
Moisture	0.4	0.5	0.6
Space	0.07	0.62	0.92

Table 20. Genetic makeup of species adaptability for *Corylus Avellana*

Condition	Lower	Preferred	Upper
Sunlight	0.4	0.5	0.6
Temperature	-6°C	20°C	36°C
Moisture	0.4	0.5	0.6
Space	0.01	0.25	0.55

Table 21. Genetic makeup of species adaptability for *Salix Babylonica*

Condition	Lower	Preferred	Upper
Sunlight	0.57	0.69	0.84
Temperature	-5°C	20°C	36°C
Moisture	0.58	0.89	0.95
Space	0.01	0.25	0.55

Table 22. Genetic makeup of species adaptability for *Dryopteris filix-mas*

Condition	Lower	Preferred	Upper
Sunlight	0.39	0.56	0.69
Temperature	-4°C	20°C	30°C
Moisture	0.08	0.21	0.62
Space	0.07	0.84	0.98

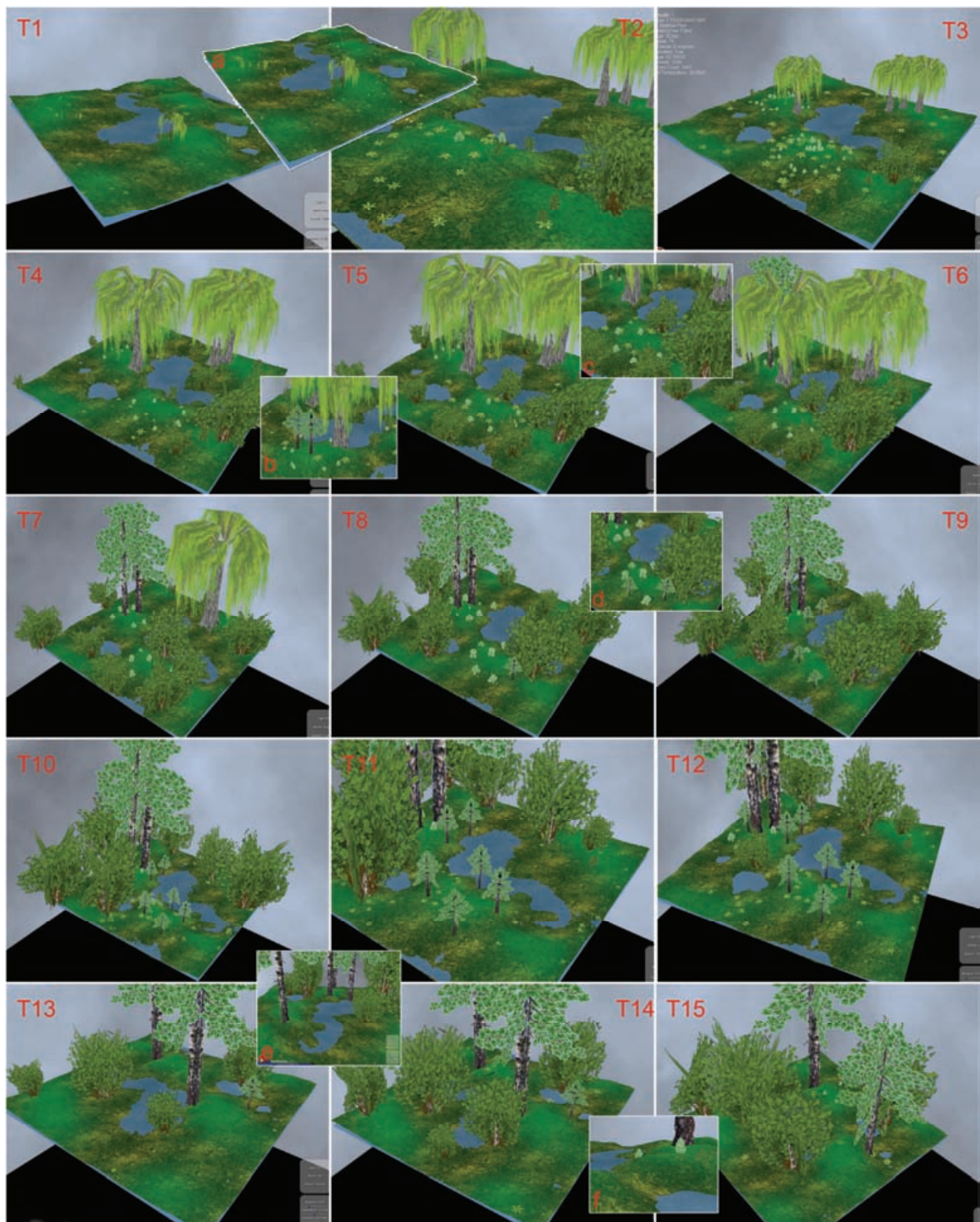


Figure 113. Growth and population amongst plants of different species

5.3.4. Species Concentration: Grouping and Competition

In this experiment, three different species of herbaceous perennials were released onto a sampling of the Shotton River valley at five metres in width and length. Three species of plants – *Urtica dioica* (Stinging Nettles), *Hieracium gronovii* L. (Hairy Hawkweed), and *Dryopteris filix-mas* (Male Ferns) were used in the landscape for observation. Adaptability for *Dryopteris filix-mas* is in Table 17. The adaptability for *Hieracium gronovii* L. and *Urtica dioica* is described in Table 23. The emerging patterns in the time steps demonstrate the adaptability and competition of the herbaceous plants. In the image sequence (Figure 114), the Stinging Nettles and Hairy Hawkweeds species dominate the landscape with equal distribution of land-use due to the similarities in the adaptability values. The scenario showed that stronger plants – plants characterised by a higher level of adaptability and larger sizes are comparatively more dominant and that plants possessing similar adaptability will have equal opportunity in the struggle for resources, issuing in equal standing in terms of their growth and numbers.

Table 23. Genetic makeup of species adaptability for *Hieracium gronovii* L. and *Urtica dioica*

Condition	Lower	Preferred	Upper
Sunlight	0.21	0.46	0.78
Temperature	4°C	20°C	30°C
Moisture	0.14	0.3	0.52
Space	0.07	0.62	0.92

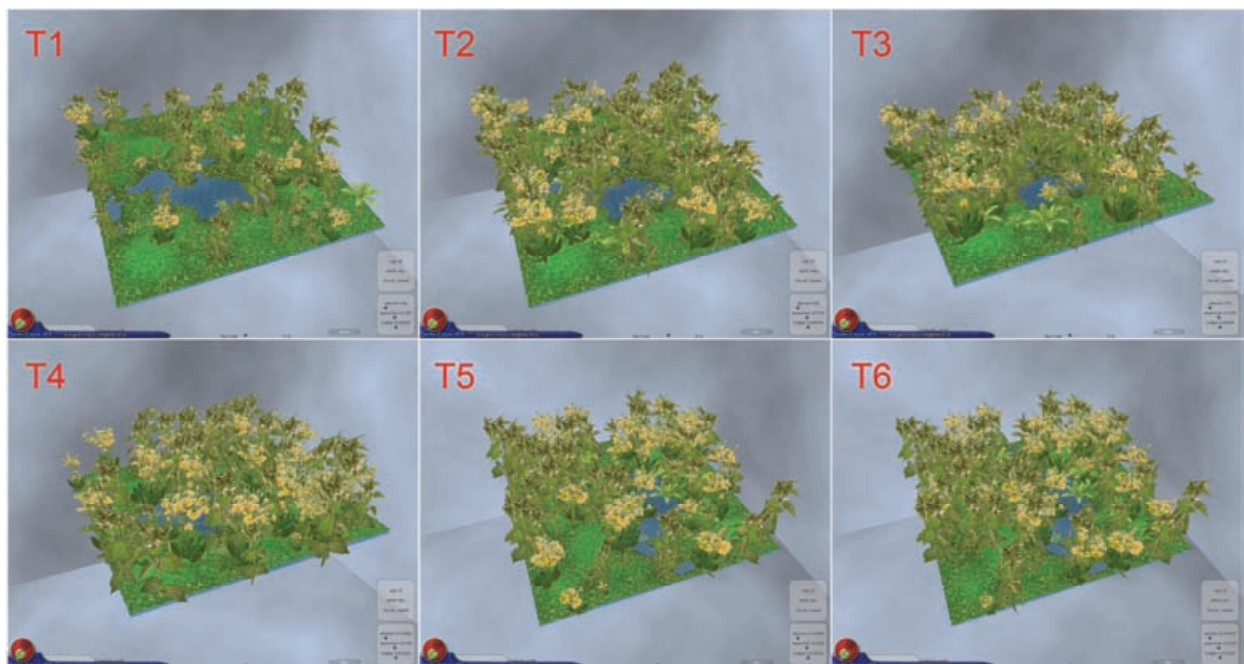


Figure 114. Herbaceous vegetation patterns on landscape demonstrating species groupings and competition

Figure 115 shows other scenarios where species grouping emerges by reason of their niches and the way they distribute their seeds.

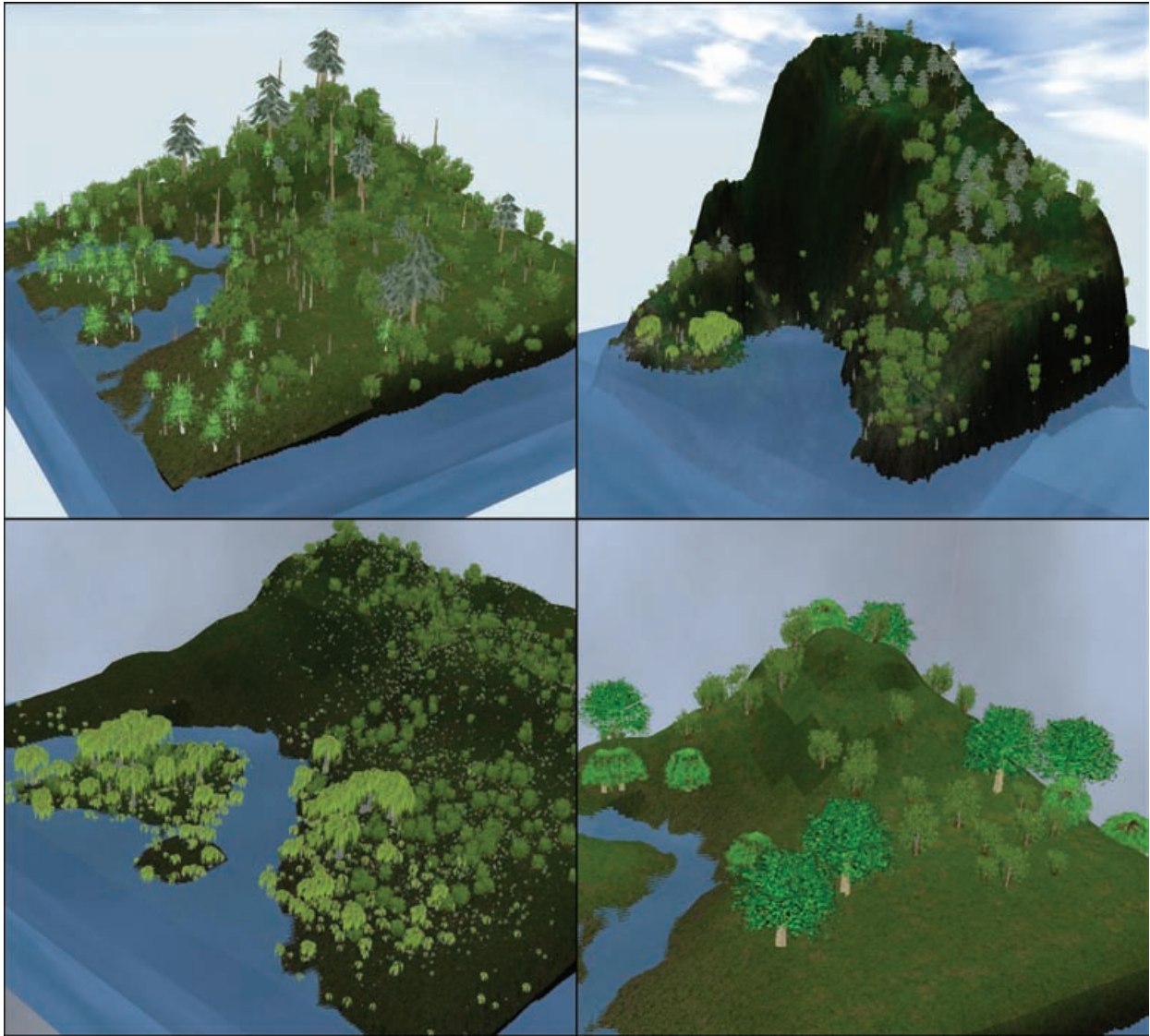


Figure 115. Various patterns on landscape demonstrating the clustering of similar species

5.3.5. Hydrology and Competition

A terrain measuring 150m² and 50m at the highest point of the landscape relative to the river was sampled from the Shotton River Valley. Equal number of seeds belonging to three species of vegetation – Pine, Hazel, and Willow were distributed across the landscape. The environmental setting simulates a typical Mesolithic landscape in the North Sea region. In the simulation (Figure 116), as virtual time progresses, seedlings belonging to the species begin germinating and growing.

At year 71 the landscape has a healthy population. Willows began forming near the river banks where the hydrology is ideal. This reflects the Willow tree's preference in the natural world. Pine and Hazel appears to have an equal distribution across the landscape. From years 116 through to 179, the Pine and Hazel begin occupying most of the spaces, 'herding' the Willow towards the lower right corner of the river banks. At year 250 the Willow species disappeared entirely from the terrain. At year 500, the Pine species dominates the landscape. Each species' characteristics and their strength and preferences towards a typical environmental setting is observed. The habitat of the Willow trees is observable near the river banks. The Hazel appeared to spread across the landscape faster than the other species, occupying spaces and competing with other plants. The Pine is a naturally slow-growing tree, even though its timeframe of growth is lengthy, spanning hundreds of years, its characteristics, adaptability, and height makes it the dominant species in the later stages of this particular scenario.

An observation of the same landscape planted only with the Willow species is drawn with a red border. In comparison with previous observations, at year 282 without competition from Pines and Hazels, the Willow species has a healthy population.

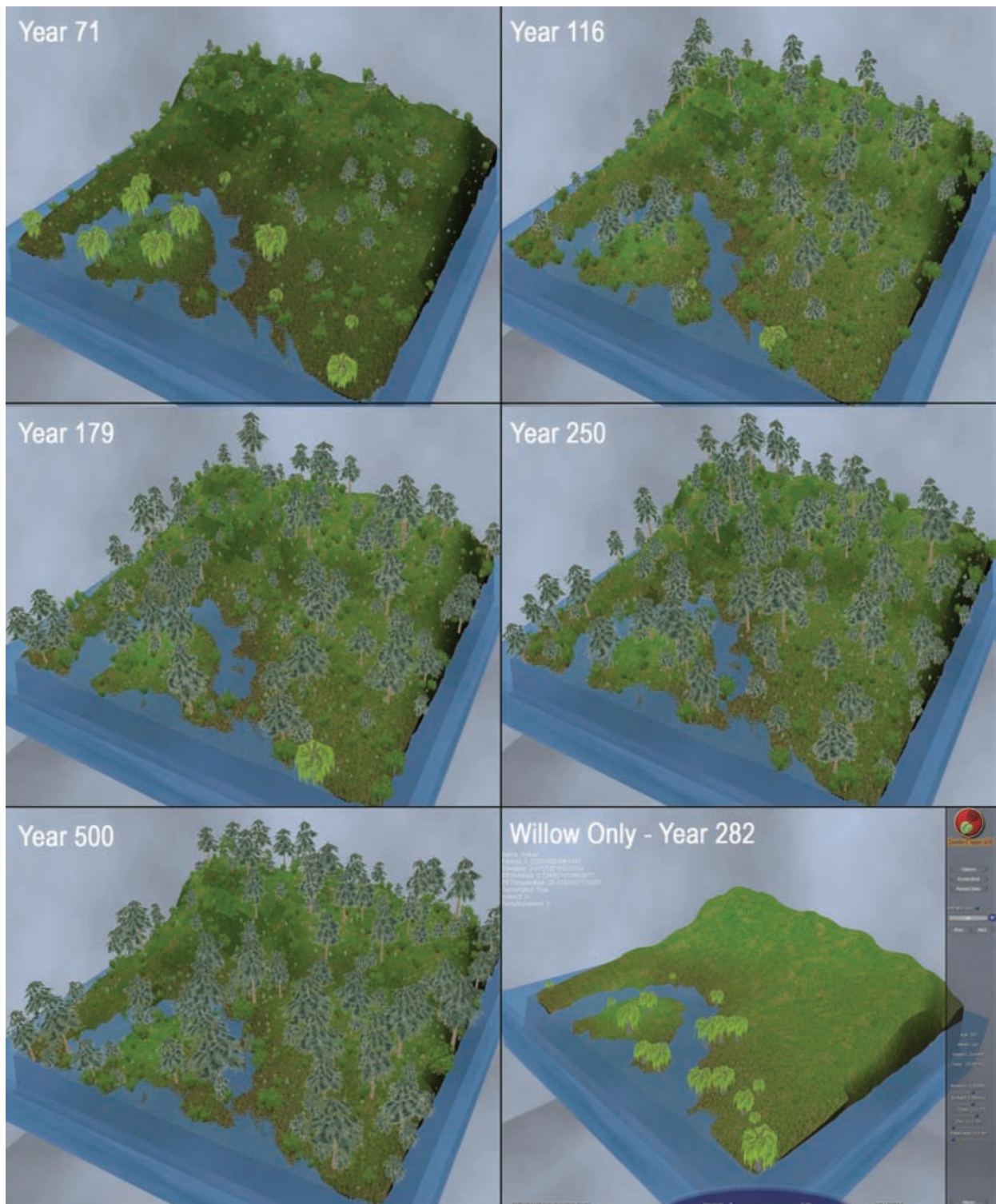


Figure 116. Hydrology and species competition – Pine, Hazel, and Willow

5.3.6. Temperature and Altitudinal Limits

In this experiment, three species of woodland types were tested for their adaptability to temperature extremes and altitudinal limits. The experiment is carried out on a landscape 200m² with an altitude of 230.5m. The temperature-altitude ratio was set to decrease by -5°C per 100 metres to demonstrate the effects. The adaptability of each species in this scenario is listed in Tables 20-22. Figure 117 are sequences of the simulation and Figure 118 contains graphs reflecting population densities in different altitudes recorded from year 35 onwards.

Table 24. Genetic makeup of species adaptability for *Pinus Sylvestris*

Condition	Lower	Preferred	Upper
Sunlight	0.4	0.5	0.7
Temperature	-20°C	9°C	35°C
Moisture	0.22	0.55	0.75
Space	0.07	0.62	0.92
Altitude	20m	728m	6394m

Table 25. Genetic makeup of species adaptability for *Corylus Avellana*

Condition	Lower	Preferred	Upper
Sunlight	0.25	0.4	0.6
Temperature	-6°C	20°C	36°C
Moisture	0.25	0.47	0.56
Space	0.01	0.25	0.55
Altitude	20m	50m	600m

Table 26. Genetic makeup of species adaptability for *Salix Babylonica*

Condition	Lower	Preferred	Upper
Sunlight	0.57	0.67	0.84
Temperature	-6°C	20°C	36°C
Moisture	0.42	0.7	0.83
Space	0.01	0.25	0.48
Altitude	5m	22m	854m

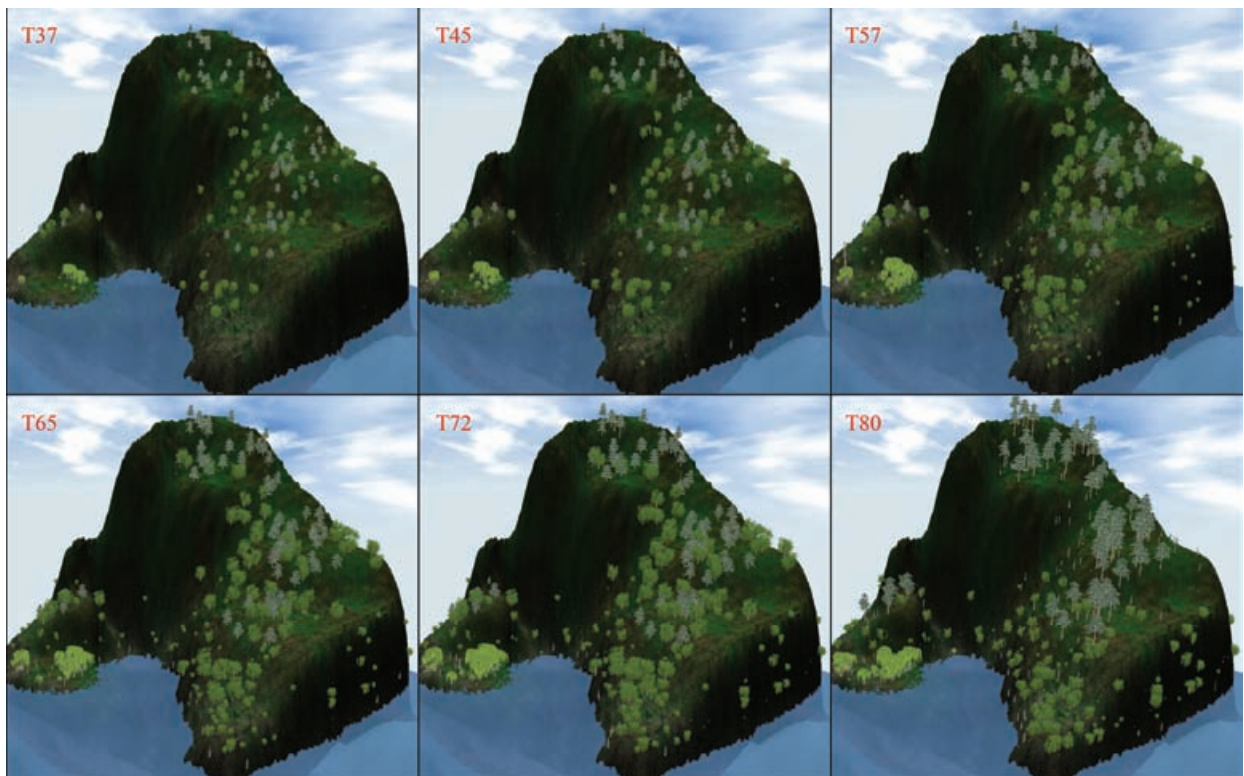


Figure 117. Temperature and altitudinal limits affecting plant species

The landscape has not reached climax community as seen in the open spaces and the population increase in the trends of the graphs. The graph showed that the population of Pine is increases in the third and fourth divisions and fluctuates in the first division. The number of Hazel remained relatively the same in the third and fourth divisions while the first and second divisions showed a gradual population increase in the species. Willow exists only in the first and second divisions with a higher rate of increase in the first divisions near sources of water.

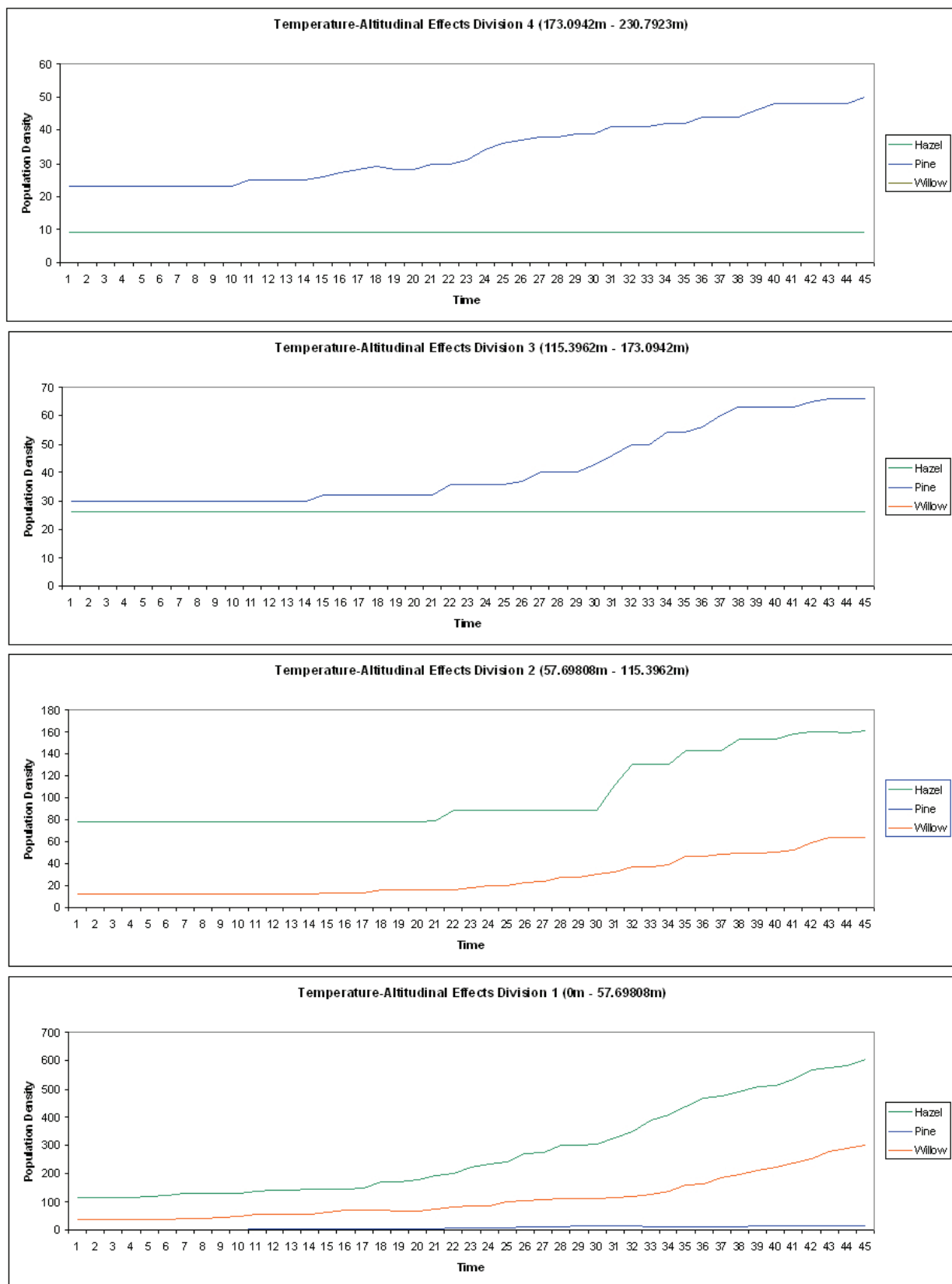


Figure 118. Temperature-altitudinal effects graph showing plant population in four different divisions of the landscape

5.3.7. Effects of Sunlight and Shade

This experiment deals with the effects of sunlight and shade on different species of plants. In particular, the species growing in the undergrowth such as Ferns, Hairy Hawkweed, and Stinging Nettles are observed. Large trees such as *Betula* (Birch) and *Quercus* (Oak) are used as shade canopies. The genetic makeup of each species are listed in the tables below. Initially seeds and seedlings of Ferns, Hairy Hawkweed, Stinging Nettle, and Birch were scattered across the 20m² terrain (Figure 119). At T6, Birch seedlings have grown to a visible extent. The three earlier species did not survive the harsh sunlight. Two 250 year old Oaks are planted on the landscape, of which one died immediately due to competition from the stronger tree. Ferns are re-introduced at year 10, Stinging Nettles at year 15, and Hairy Hawkweed at year 18. The latter two species persist for a little while and expired soon after year 25. The Ferns however begin spreading under the shade of the Oak tree. At T29, the two Birches under the oak tree expired due to competition for sunlight from the larger Oak tree. At year 26 the water level is lowered to create a more suitable condition for Birch seeds to germinate. At T38, a seed from the nearby Birch tree germinated (seen at foreground of T47). At T47, as the trees grow, the Ferns found their niches under the forest canopy, spreading from the Oak tree to the undergrowth of the clusters of Birches.

Table 27. Genetic makeup of species adaptability for *Hieracium gronovii* L. and *Urtica dioica*

Condition	Lower	Preferred	Upper
Sunlight	0.4	0.46	0.98
Temperature	4°C	20°C	30°C
Moisture	0.14	0.3	0.52

Table 28. Genetic makeup of species adaptability for *Dryopteris filix-mas*

Condition	Lower	Preferred	Upper
Sunlight	0.09	0.45	0.85
Temperature	-4°C	20°C	32°C
Moisture	0.1	0.21	0.62

Table 29. Genetic makeup of species adaptability for *Betula*

Condition	Lower	Preferred	Upper
Sunlight	0.33	0.5	0.98
Temperature	-6°C	20°C	30°C
Moisture	0.35	0.5	0.6

Table 30. Genetic makeup of species adaptability for *Quercus*

Condition	Lower	Preferred	Upper
Sunlight	0.3	0.69	1
Temperature	-6°C	20°C	36°C
Moisture	0.32	0.45	0.66

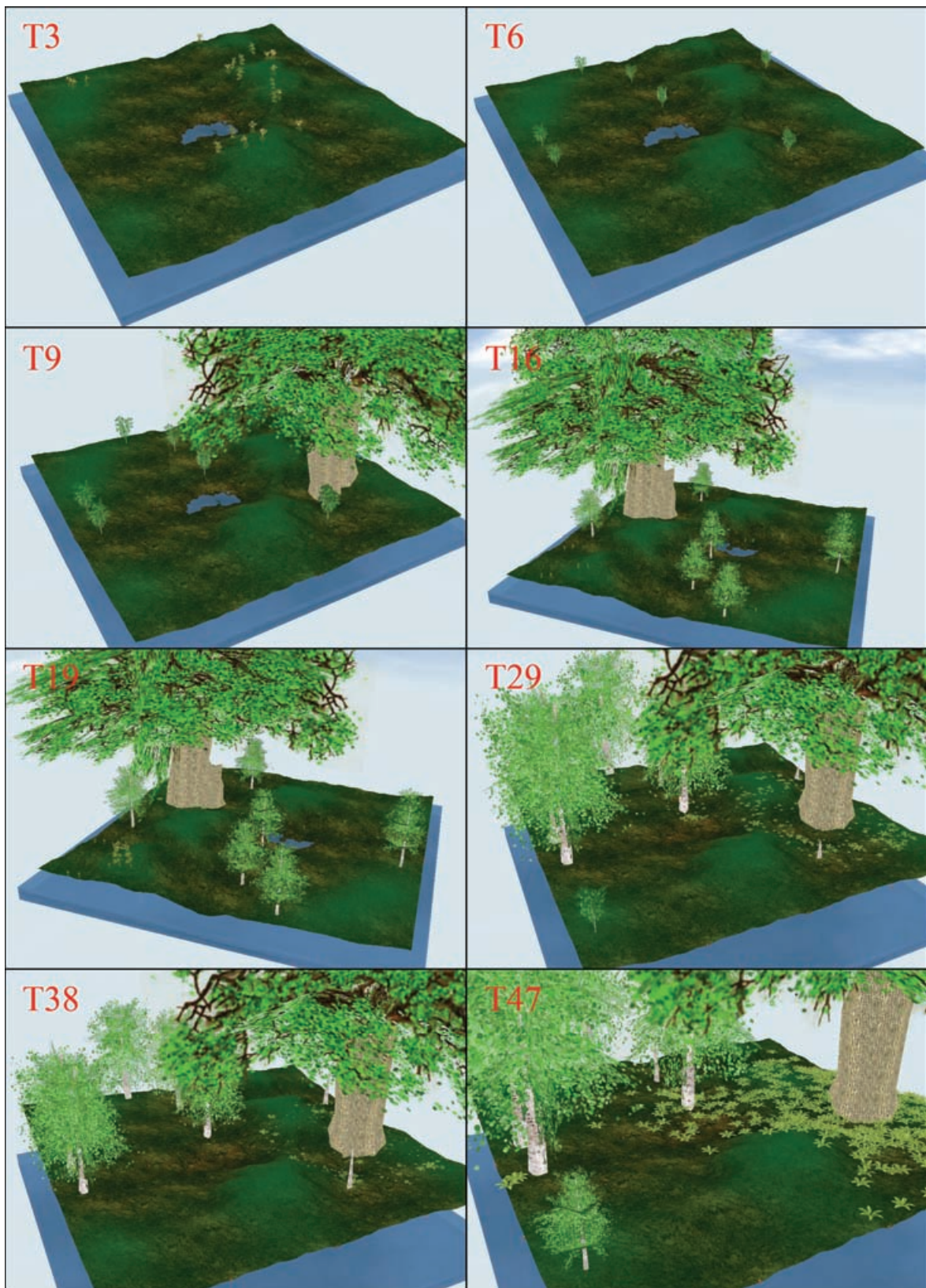


Figure 119. Effects of sunlight and shade among species in the undergrowth

5.3.8. Plant Decay

The structures of dead trees and plants pass through a process of gradual decay. The rotting structures add nutrients to the ground and provide a good habitat for the undergrowth and young plants. Figure 120 shows a forest simulation of different species of plants and the different levels of decaying stumps.



Figure 120. Effects of sunlight and shade among species in the undergrowth

5.3.9. Ecotones and Ecoclines

In landscape ecology, an ecotone is the transitional zone between two communities [334]. Examples of natural ecotones include the transitions from forest to open grasslands, forest to marshlands, or land-water transitions. An ecotone contains species from adjacent zones but often contains species not found in the adjacent communities. A characteristic of an ecotone is the richness of species [335]. An ecocline is landscape boundary where a gradual change in

environmental conditions occurs. This continuous change causes the distribution of species across the boundary because certain species survives better under certain conditions [336].

Ecotones and ecoclines can be observed throughout the simulation exercises. In section 5.2.4, three species of vegetation thrives in different ecoclines. Division 5 of Figure 99 and Figure 100 shows the blue species clearly thriving in the extremes of a cold habitat where the population of the green and red species declined. In division 1, the red species survives better than the other species. Divisions 2, 3, and 4 show the characteristic of an ecotone with richness of species. The boundary is more apparent if the terrain is enlarged and more species included.

Section 5.2.5 to 5.2.6 and 5.2.8 shows horizontal versions of ecotones and ecoclines. The zones on the landscapes where the concentration of a single species occurs are ecoclines. The transitional boundaries between each zones characterised by species richness are ecotones. In a vertical version in section 5.2.7, the various slope conditions of a landscape provided different niches for each species. The graphs in Figure 12 illustrate a gradual transition from an ecocline to an ecotone.

Examples of ecotones and ecoclines containing real plant representations can be seen in sections 5.3.4 to 5.3.7.

5.4. Conclusion

There are at least two ways of verifying Artificial Life model in the context of this research. The former verifies the model via global and local comparisons of vegetation behaviours, patterns of distribution and their preferences to ecological characteristics and environmental changes. The second approach verifies the model with pollen records from the same region and is covered in the next chapter. The results of the former approach investigated in this chapter have shown that correlations exist between alife-based vegetation and their natural counterpart. In particular, characteristics known to occur in the interaction of vegetation communities and the effects of environmental changes were observed in the detailed study of the alife model within the simulated Virtual Environment:

- Vegetation species migrate due to environmental changes
- Population density of certain species increases in ecological niches deemed habitable to that species.
- Seed reproduction and germination occurs based on local conditions
- Crowd tolerant plants thrive in compact spaces
- Crowd intolerant plants are disadvantageous in their growth, reproduction, and distribution
- Shade tolerant plants constitute the undergrowth of forest canopies
- Survival and reproduction of species found to occur more frequently in available spaces and patches of terrain where larger plants have died and are decaying
- Smaller plants are at a disadvantage in comparison to larger plants due to competition for space and sunlight
- Plants able to adapt persist across generations
- Similar species are observed to cluster into community over time
- Migrations of species suited to the local environment are observed to populate available spaces quickly, causing the decline of existing weaker species.
- Formation of ecotones and ecoclines

The experimental studies have shown that synthesising vegetation with simple rules built into the alife model can become a potentially useful model for reconstructing ancient landscapes. The next chapter applies the model described in Chapter 4 and verified in this chapter to Mesolithic scenarios and the Shotton River Valley.